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Anti-icing System For Wind Turbine Blades By Using Microwave Energy Absorption

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Abstract

The accumulation of ice on wind turbine blades, particularly in cold climates, presents significant challenges to electric energy production and turbine reliability, leading to the use of ice protection systems integrated in the blades. This dissertation explores the feasibility of an alternative to the current anti-icing solutions for wind turbine blades, by using microwave energy absorption. A comprehensive literature review was conducted on wind turbines, ice formation, and current anti-icing and de-icing systems. The study analysed microwave generation, propagation, absorption, and heating mechanisms to understand the investigated technology, and reviewed the current state of microwave anti-icing systems, focusing on its implementation in the wind energy sector.

The study began by examining how microwave heating has been modeled in multiphysics software in previous research, which was essential for developing initial models. Simple microwave oven models, developed in COMSOL, were compared with the literature and used as a foundation for further development of numerical models of a microwave anti-icing system.

The proposed solution involved microwave generation within the blade, emission towards an absorbing material that converts electromagnetic energy into heat, and subsequent heat diffusion to raise the blade's surface temperature. Various designs for the system integration inside the blade were proposed, with the use of a microwave absorbing layer embedded in the blade laminate identified as the most effective solution for microwave absorption and surface heating.

Power requirements for the anti-icing system were determined by a developed model in EES. System constraints were set with a maximum power supply of 93.3 kW per blade and a maximum blade temperature of 55°C. A deep study identified suitable materials for the microwave absorbing layer, focusing on the properties that enable efficient conversion of microwave energy into heat.

Building on the initial microwave oven models, four simplified microwave anti-icing system models were developed in COMSOL: two 3D flat plate transient models - one focusing on the microwave absorbing layer and the other incorporating blade materials - and two 2D wind turbine blade cross-section transient models - one with a constant convection coefficient and the other, more realistic, with CFD analysis. These models were compared with a transient-state model developed in EES which estimates temperature variations within the blade laminate.

A specific design was studied in more detail: multiple magnetrons inside the blade, emitting microwave energy towards the absorbing material. The most suitable absorber, Eccosorb BSR-1, was selected based on its superior performance. The absorbing layer was optimized with a thickness of 3 mm and placed near the surface, achieving 98.5% absorption efficiency at 2.45 GHz. Under harsh atmospheric conditions where anti-icing is possible, the system met power and temperature constraints, and a maximum spacing of 0.5 m between sources with 1.5 kW per magnetron was obtained. For a 70 m blade, the system increased the blade's mass by less than 3-5% and total investment costs were estimated between 200 and 380 k€. This preliminary analysis demonstrated the system's ability to efficiently heat the blade surface, although heat distribution and system's durability, along with design optimization and risks analysis, require further investigation in order to develop a system capable of competing with established technologies.

Keywords: microwaves, anti-icing, wind turbines, heat transfer, numerical model.

Resumo

A acumulação de gelo nas pás das turbinas eólicas apresenta obstáculos significativos à produção de energia elétrica e ao funcionamento das turbinas, sendo necessários sistemas de proteção contra o gelo integrados nas pás. Esta dissertação explora a viabilidade de uma alternativa às atuais soluções anti-gelo para turbinas eólicas, utilizando absorção da energia das micro-ondas. Foi efetuada uma revisão exaustiva da literatura sobre turbinas eólicas, formação de gelo e sistemas atuais de anti-gelo. Foram analisados os mecanismos de geração, propagação, absorção e aquecimento por micro-ondas de forma a compreender a tecnologia investigada, estudando-se o estado atual dos sistemas anti-gelo por micro-ondas e a sua implementação no sector da energia eólica.

Começou-se por examinar como o aquecimento através de micro-ondas foi modelado numericamente em investigações anteriores, possibilitando o desenvolvimento de modelos iniciais. Estes modelos, desenvolvidos no COMSOL, foram comparados com a literatura e utilizados como base para o desenvolvimento posterior de modelos numéricos de um sistema anti-gelo por micro-ondas.

A solução proposta envolve geração de micro-ondas no interior da pá, emissão para um material que absorve a energia electromagnética e a converte em calor, e difusão do calor para aumentar a temperatura da superfície da pá. Foram propostos vários designs para a integração do sistema no interior da pá, definindo-se o uso de uma camada absorvente de micro-ondas, incorporada no laminado da pá, como a solução mais eficaz para o aquecimento da superfície.

Os requisitos de potência para o sistema foram determinados através de um modelo desenvolvido no EES. Estabeleceram-se restrições de potência máxima (93,3 kW por pá) e temperatura máxima da pá (55°C). Foram também seleccionados materiais adequados para a camada absorvente, com propriedades que permitem uma conversão eficiente da energia de micro-ondas em calor.

Com base nos modelos iniciais desenvolvidos, foram obtidos quatro modelos de sistemas simplificados de anti-gelo por micro-ondas no COMSOL: dois modelos de placa plana 3D - um centrado na camada absorvente de micro-ondas, e outro incorporando os materiais da pá - e dois modelos 2D da secção transversal de uma pá - um com um coeficiente de convecção constante e o outro com análise CFD. Estes modelos foram comparados com um modelo em regime transiente desenvolvido no EES que estima as variações de temperatura no interior do laminado da pá.

Foi estudado um design específico: vários magnetrons no interior da pá, emitindo micro-ondas para o material absorvente seleccionado - Eccosorb BSR-1. A camada absorvente foi otimizada com uma espessura de 3 mm e colocada perto da superfície, atingindo 98.5% de eficiência de absorção a uma frequência de 2,45 GHz. Em condições atmosféricas onde é possível o funcionamento do sistema, este cumpriu as restrições estabelecidas, obtendo-se um espaçamento máximo de 0,5 m entre fontes com 1,5 kW. Para uma pá de 70 m, o sistema aumentou a massa em menos de 3-5% e os custos iniciais foram estimados entre 200 e 380 k€. Esta análise preliminar demonstrou que o sistema é capaz de aquecer eficazmente a superfície da pá, embora a distribuição do calor e a durabilidade do sistema, assim como a otimização do design e uma análise aos riscos, exijam uma investigação mais aprofundada para desenvolver um sistema capaz que consiga competir com as tecnologias estabelecidas.

Palavras-chave: micro-ondas, anti-gelo, turbinas eólicas, transferência de calor, modelo numérico.

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Pedro Dias

*“Because your question searches for deep meaning,
I shall explain in simple words.”*

Dante Alighieri

Contents

Nomenclature	xiii
List of Figures	xvii
List of Tables	xxi
1 Introduction	1
1.1 Context and Motivation	1
1.2 Vestas	2
1.3 Objectives	3
1.4 Structure of the Dissertation	4
2 State of the Art	5
2.1 Background	5
2.2 Wind Turbines	6
2.3 Ice formation	9
2.4 Anti-icing and De-icing Systems	12
2.4.1 Passive Technology	13
2.4.2 Active Technology	14
2.5 Microwaves	18
2.5.1 Microwave Propagation	19
2.5.2 Microwave Absorption	20
2.6 Microwave Heating	21
2.6.1 Microwaves Generators	23
2.6.2 Microwaves Absorbers	25
2.7 Microwave Anti-icing and De-icing	27
2.7.1 Concept	27
2.7.2 Current State of the Art Overview	28
3 Initial Modeling and Validation	35
3.1 Objectives and Motivation	35
3.2 Introduction to COMSOL Multiphysics	36
3.3 Microwave Ovens 3D Models	36
3.3.1 Simulation Setup and Parameters	38
3.4 Results and Validation	40
3.4.1 Study 1	40
3.4.2 Study 2	41
3.4.3 Study 3	42

4	Microwave Anti-icing Solution	45
4.1	Objectives and Methodology	45
4.2	Proposed Solution and Possible Designs	46
4.2.1	Working Principle	46
4.2.2	Proposed Designs	47
4.3	Anti-icing System Requirements	48
4.3.1	EES Steady-State Model	49
4.3.2	System Constraints	50
4.4	MAL Material Selection	51
4.4.1	Criteria for Material Selection	51
4.4.2	Description of Selected Materials and Their Properties	52
4.5	Material Comparison	52
4.5.1	Simulations on Validated Models	53
4.5.2	Influence of Thickness for Each Material	56
5	Simplified Microwave Anti-icing System Models	57
5.1	Simplified Blade Geometry	57
5.1.1	Adaptation of Initial Models	58
5.1.2	Microwave Absorbing Layer Model	59
5.1.3	Blade Materials Integration Model	63
5.2	2D Airfoil Model	66
5.2.1	Constant Convection Coefficient	66
5.2.2	CFD Simulation	69
5.3	Comparison of Results with EES Transient Model	74
6	Discussion of System Viability	77
6.1	Summary of the Analysis to the Simplified Blade Models	77
6.2	Analysis of a System Potential Design	78
6.2.1	Microwave Absorption by the MAL	79
6.2.2	Microwave Generation and Emission	85
6.3	Verification of Requirements and Constraints	89
6.3.1	System Power	89
6.3.2	System Temperature	92
6.3.3	System's Mass	95
6.4	Financial Analysis	95
6.5	Comparison with Current Anti-icing Systems	96
6.5.1	Energy Consumption	97
6.5.2	Heating Times	97
6.5.3	Heat Distribution	97
6.5.4	Investment Costs	98
6.5.5	Reliability	98
6.5.6	Weight	98
7	Conclusions	99
7.1	Main Conclusions of the Dissertation	100
7.2	Study Limitations and Future Works	102

A	Mathematical Formulation	103
A.1	Electromagnetic Fields	103
A.2	Electromagnetic Heating	106
A.3	Microwave Absorption	108
A.3.1	Absorption Parameters	109
B	Boundary Conditions of Microwave Heating Models in COMSOL	115
B.1	Port	115
B.2	Impedance boundary condition	116
B.3	Thermal Insulation Boundary Condition	116
B.4	Heat Flux Boundary Condition	116
C	Materials Properties Used by Each Study - Benchmarking	117
D	Assumptions and Iterations Made for Initial Models	119
E	Absorption Parameters Calculated with Study 1 Material Properties	125
F	Comparison Between Obtained Results in Initial Models and Reference Models	127
G	3D Designs of Microwave Anti-icing System Using Other Airfoils	131
H	EES Steady-state Model	133
I	Selected Microwave Absorbing Materials Properties	137
J	RL and Z Variations with Thickness for the Selected Materials	139
K	Adaptation of Initial Models - geometries	141
L	Mesh Refinement Analysis for The Developed Models in This Dissertation	143
L.1	Adaptation of Initial Models	143
L.2	MAL Model	144
L.3	BMI Model	145
L.4	2D Airfoil Model - Constant Convection Coefficient	145
L.5	2D Airfoil Model - CFD	145
M	EES Transient Model	147
N	Comparison of Temperatures Variations With Time for EES Transient Model and COMSOL Models	151
O	Maximum Spacing Between Microwave Sources - MAL Model Simulations	153
P	Process and Calculations to Obtain the Power of the Microwave System	155
	References	157

Nomenclature

Abbreviations

2D	Two dimensions
3D	Three dimensions
AL ₂ O ₃	Alumina
BMI	Blade Material Integration
CAPEX	Capital Expenditure
CCFRP	Continuous carbon fiber reinforced polymer
CFD	Computational Fluid Dynamics
CFRP	Carbon fibre reinforced polymer
CNT	Carbon Nanotube
EES	Engineering Equation Solver
FEM	Finite Element Method
GFRP	Glass fibre reinforced polymer
GTT	Glass Transition Temperature
HAWT	Horizontal-axis wind turbine
HR1	Heating region 1 in the airfoil
HR2	Heating region 2 in the airfoil
HSS	High-speed Shaft
IBC	Impedance boundary condition
LSS	Low-speed Shaft
LWC	Liquid Water Content
MA	Metamaterial Absorber
MAL	Microwave Absorbing Layer
MVD	Median Volume Diameter
MWCNT-epoxy	Multi-walled carbon nanotubes dispersed in an epoxy
MWCNT-PP	Multi-walled carbon nanotubes dispersed in a polypropylene matrix
(NBSiC)p	Porous nitride bonded silicon carbide
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PBC	Port boundary condition
PDMS	Polydimethylsiloxane
PET	Polyethylene Terephthalate
PML	Perfectly Matched Layer
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
RF	Radio-frequency

ROI	Return on investment
RPM	Rotations per minute
SBC	Scattering Boundary Condition
Si ₃ N ₄	Silicon Nitride
SiC	Silicon Carbide
SPL	Lightning protection layer
TEM	Transverse Electromagnetic
TE	Transverse Electric
VAWT	Vertical-axis wind turbine

List of Variables

Variable	Designation	Unit
A	Area of the blade heated surface	m ²
A_s	Swept area	m ²
a	Arc length corresponding to the heated blade surface	m
B	Magnetic flux density	T
C_p	Power coefficient	-
c	Chord length of the airfoil	m
c_e	Velocity of electromagnetic waves	m/s
c_p	Specific heat capacity of a material	J/(kg · K)
D	Electric flux density or electric displacement field	C/m ²
D_f	Field penetration depth or skin depth	m
D_p	Penetration depth	m
d	Thickness of the absorber	m
E	Electrical field	V/m
e	Surface emissivity	-
f	Microwave frequency	Hz
f_c	Cutoff frequency	Hz
h	Convection heat transfer coefficient	W/(m ² · K)
h_{ext}	Exterior heat convection coefficient	W/(m ² · K)
h_m	Average convection heat transfer coefficient	W/(m ² · K)
H	Magnetic field	A/m
J	Electric current density	A/m ²
k	Thermal conductivity of a material	W/(m · K)
k_0	Free space wave number	rad/m
k_f	Thermal conductivity of the fluid	W/(m · K)
L	Characteristic length of the flow	m
L_p	Length of the flat plate	m
m	Mass	kg
P	Electromagnetic power dissipated per unit volume	W/m ³
P_{ave}	Time-average Poynting vector	W/m ²
P_p	Poynting vector	W/m ²
P_{turb}	Power transmitted to the turbine	W
P_{upst}	Power available upstream of the turbine	W
Pr	Prandtl number	-
$\dot{q}$	Internal heat generation	W/m ³
$\dot{q}_c$	Convective heat flux	W/m ²

$\dot{q}_{rad}$	Radiation losses per unit area	W/m ²
R	Reflection coefficient	-
Re	Reynolds number	-
RL	Reflection loss	dB
r	Blade radial length	m
S	Phasor Poynting vector	W/m ²
T	Temperature	°C
T_{∞}	Ambient temperature	°C
T_{sup}	Blade surface temperature	°C
$\tan \delta$	Loss tangent or loss angle constant	-
$\tan \delta_{\epsilon}$	Ratio of the imaginary and the real parts of permittivity	-
$\tan \delta_{\mu}$	Ratio of the imaginary and the real parts of permeability	-
V_f	Fluid velocity	m/s
V_o	Wind speed upstream of the rotor	m/s
V_r	Fluid relative velocity	m/s
V_{tan}	Tangential velocity of the blade	m/s
Z	Degree of impedance matching	-
Z_0	Impedance of free space	Ω
Z_i	Impedance of the absorber	Ω

Greek letters

α	Attenuation factor or attenuation	Np/m
β	Phase constant	rad/m
ϵ_s	Permittivity at a frequency approaching zero	-
ϵ_{∞}	Permittivity at a frequency approaching infinity	-
γ	Propagation constant	rad/m
λ_0	Microwave wavelength in free space	m
μ	Permeability	H/m
$\mu''_{eddy\ current}$	Magnetic loss factor due to eddy currents	-
μ_f	Dynamic viscosity of the fluid	Pa · s
$\mu''_{hysteresis}$	Magnetic loss factor due to hysteresis	-
μ_0	Permeability of free space	H/m
μ_r	Complex relative permeability	-
μ'_r	Real part of relative permeability or relative magnetic constant	-
μ''_r	Imaginary part of relative permeability or relative magnetic loss factor	-
$\mu''_{resonance}$	Magnetic loss factor due to resonance	-
ν	Kinematic viscosity of the fluid	m ² /s
ρ	Density of a material	kg/m ³
ρ_{air}	Air density	kg/m ³
ρ_f	Fluid density	kg/m ³
ρ_v	Electric volume charge density	C/m ³
σ	Electrical conductivity	S/m
σ_s	Stefan-Boltzmann constant	W/(m ² · K ⁴)
τ	Relaxation time	s
ϵ	Permittivity	F/m
ϵ_0	Permittivity of free space	F/m

ε_r	Complex relative permittivity	-
ε'_r	Real part of relative permittivity or relative dielectric constant	-
ε''_r	Imaginary part of relative permittivity or relative dielectric loss factor	-
ε_p	Polarization contribution to the relative permittivity	-
ε'_p	Polarization contribution to the real part of relative permittivity	-
ε''_p	Polarization contribution to the imaginary part of relative permittivity	-
ε''_c	Conduction contribution to the imaginary part of relative permittivity	-
ω	Microwave angular frequency	rad/s
ω_r	Blade angular rotational speed	rad/s

List of Figures

1.1	Two different examples of ice accumulation on wind turbine blades [4, 6].	2
2.1	Wind turbine components [19].	6
2.2	Cross-section of a wind turbine blade. Adapted from [21].	8
2.3	Rime ice formation on a wind turbine blade [28].	10
2.4	Glaze ice on aircraft wings [29, 30].	11
2.5	Frost formation on an aircraft wing [31].	12
2.6	Ice accretion and distribution.	12
2.7	The principle of pneumatic de-icing technique, placed on the leading edge of the blade [34].	15
2.8	Schematic of Vestas' heating resistance anti-icing system [36].	16
2.9	Hot circulating air technology from ENERCON [37].	17
2.10	Air layer configuration and heat transfer mechanism [3].	18
2.11	Microwaves in the electromagnetic spectrum [42].	19
2.12	Reflection process between an electromagnetic wave and an absorber [47].	20
2.13	Magnetron schematic for generation of microwave radiation. [55].	24
2.14	Schematic of the ice prevention system proposed by Robert J. Hansman (20 - heating region; 21 - wing; 33 - directional coupler; 34 - oscillator; 35 - antennas) [62].	29
2.15	Schematic of one of the configurations proposed by LM Glasfiber, where the microwave generators are placed on the blade root (2 - blade; 6 - microwave generators; 7 - horn antennas). Adapted from [63].	30
2.16	Schematic of the structure's configuration proposed by Lambert Feher, in 2002 (CFK corresponds to the carbon fiber). Adapted from [64].	30
2.17	Representation of a wind turbine blade anti-icing system using a microwave-absorbent coating [65].	31
2.18	Microwave absorbing (susceptor) layer placement on the wind turbine blade [67].	32
2.19	Test chamber representation of the Design Laboratory investigation [67].	32
2.20	Schematic representation of the system proposed by Zehai Zhang et al. in a portion of the wind turbine blade [69].	34
3.1	3D Models of the selected studies. 1 - cavity; 2 - waveguide; 3 - base; 4 - absorber; 5 - glass plate.	38
3.2	Results obtained for model based on Study 1.	41
3.3	Results obtained for model based on Study 2.	42
3.4	Comparison of the maximum temperature variation between simulation of the present work, and simulation/experimental results from study 2.	43
3.5	Results obtained for model based on Study 3.	43

3.6	Comparison of the maximum temperature variation between simulation of the present work, and simulation/experimental results from study 3.	44
4.1	Main phases of the microwave anti-icing system.	46
4.2	Lightning protection layer positioning relative to the MAL.	47
4.3	Microwave transport and emission through slotted waveguides.	48
4.4	Microwave generation and emission through magnetrons along the blade.	49
4.5	Required power to keep the blade surface steady-state temperature at least at 5 °C, as a function of wind relative velocity.	50
4.6	Power loss and absorption efficiency for the selected materials, for Model based on Study 2.	53
4.7	Power loss and absorption efficiency for the selected materials, for Model based on Study 3.	54
4.8	Maximum temperatures reached by each selected material, in both models.	54
4.9	Maximum temperature difference within each selected material, in both models.	55
4.10	Attenuation and penetration depth of the five selected materials, at 2.45 GHz.	56
5.1	Electromagnetic power loss for each Flat Plate Model, for each absorber material.	59
5.2	MAL Model. 1 - PML; 2 - waveguide opening; 3 - MAL.	60
5.3	MAL Model power flow, for Eccosorb BSR-1. The arrow length is in logarithmic scale to facilitate visualization. The model is represented in the xz -plane.	62
5.4	Layers considered for the integration of wind turbine blade materials.	64
5.5	BMI Model power flow, for Eccosorb BSR-1. The arrow length is in logarithmic scale to facilitate visualization. The model is represented in the xz -plane.	66
5.6	Comsol setup of 2D Airfoil Model with constant convection coefficient. 1 - blade shell; 2 - waveguide; 3 - PML; 4 - port; 5 - shear web.	67
5.7	Results obtained in COMSOL for the 2D Airfoil Model using constant convection coefficient, for Eccosorb BSR-1, after 300 seconds.	69
5.8	Geometry of 2D Airfoil Model with CFD simulation. 1 - airflow domain; 2 - blade shell; 3 - shear web; 4 - waveguide; 5 - PML domain. c is the chord length.	70
5.9	Airflow velocity in 2D Airfoil Model with CFD.	72
5.10	Arc length (a) where the temperature distribution along the blade surface is evaluated.	73
5.11	Variation of temperature along the blade surface, for the two 2D models.	73
6.1	Two alternatives for the region of the airfoil where the MAL is embedded in the laminate.	81
6.2	Temperature distribution along the blade surface, for the considered arc length (a), for different placement of the MAL.	81
6.3	Influence of the MAL thickness on power absorption efficiency, for each absorber.	82
6.4	Variation of power required per microwave generation unit with number of units, for different ambient temperatures and relative wind velocity.	87
6.5	Heating times to reach 5 °C, calculated with the EES Transient Model, using 3mm of Eccosorb BSR-1 in the MAL, for ambient temperature of -10 °C.	91
6.6	Heating times to reach 5 °C, calculated with the EES Transient Model, using 3mm of Eccosorb BSR-1 in the MAL, for ambient temperature of -20 °C.	92
6.7	Results obtained in COMSOL for the 2D Airfoil CFD Model, with optimized parameters, for 600 seconds of simulation time.	93

6.8	Temperature distribution along the blade surface, after 10 minutes, for the considered arc length (a), for the critical conditions and a power of 4.78 kW/m.	94
D.1	Electric field distribution obtained with $\epsilon_{r,alumina} = 1$ (a) and from Study 1 (b). . .	121
D.2	Temperature distribution obtained with laminar airflow modeling (a) and from Study 1 (b).	121
E.1	Absorption parameters calculated with Study 1 material properties.	126
F.1	Comparison of electric field, resistive loss, and temperature distributions, between the developed model and Study 1 model.	128
F.2	Comparison of temperature field distribution and maximum temperature between the developed model and Study 2 model.	129
F.3	Comparison of electric field distribution between the developed model and Study 2 model.	129
F.4	Comparison of electric field, power loss, and temperature distributions, between the developed model and Study 3 model.	130
G.1	Microwave transport and emission through slotted waveguides (airfoil NACA 2412). . .	131
G.2	Microwave generation and emission through magnetrons along the blade (airfoil NACA 2412).	132
H.1	Equations used in EES steady-state model.	135
H.2	Parametric table used in EES steady-state model.	135
J.1	RL and Z variation with thickness for (NBSiC)p.	139
J.2	RL and Z variation with thickness for MWCNT-PP.	139
J.3	RL and Z variation with thickness for CCFRP.	140
J.4	RL and Z variation with thickness for MWCNT-epoxy.	140
J.5	RL and Z variation with thickness for Eccosorb BSR-1.	140
K.1	Flat Plate Models geometry. The absorber is highlighted in blue.	142
M.1	Heat balances equations in EES transient model.	149
M.2	Example of results obtained for each layer temperature after integration.	149
N.1	Temperature variation with time for EES Transient, BMI, and 2D with constant h_{ext} Models, using MWCNT-PP in the MAL.	151
N.2	Temperature variation with time for EES Transient, BMI, and 2D with constant h_{ext} Models, using CCFRP in the MAL.	152
N.3	Temperature variation with time for EES Transient, BMI, and 2D with constant h_{ext} Models, using Eccosorb BSR-1 in the MAL.	152
O.1	Electromagnetic power loss distribution in the absorber, for the MAL Model, using three flat plate lengths.	154
P.1	3D blade representation with the five regions considered for the power analysis, with the respective length.	155

List of Tables

2.1	Materials classification in microwave heating. Adapted from [46]	25
3.1	General information about the selected studies	37
3.2	Parameters of each study (frequency-transient study is represented by FT)	39
3.3	Comparison between results obtained and simulation results from study 1	41
3.4	Comparison between results obtained and simulation results from study 2	42
3.5	Comparison between results obtained and simulation results from study 3	44
4.1	Selected materials with descriptions. Weight percentage - wt%; Volume fraction - vf%	52
4.2	Optimal thickness for selected materials with respective RL and Z	56
5.1	Results obtained in the simulations of different absorbers in the MAL Model . . .	61
5.2	Properties and thicknesses of the different layers. Values with "est." were estimated	64
5.3	Results obtained in the simulations of the three absorbers in the BMI Model, after 300 seconds	65
5.4	Results obtained in the simulations of the three absorbers in the 2D Airfoil Model with constant convection coefficient, after 300 seconds	68
5.5	Results obtained in the simulations of the three absorbers in the 2D Airfoil Model with CFD	72
5.6	Input powers of each model, for the three absorbers under analysis, necessary to achieve the required power absorbed for the specified conditions	75
5.7	Comparison of blade surface and MAL average temperatures at 300 seconds of simulation	76
6.1	Comparison of different placements of the MAL within the blade laminate, using EES Transient Model results after 900 seconds	80
6.2	MAL mass calculations for the three absorber materials	83
6.3	Power requirements for different scenarios	91
6.4	Estimation of total investment costs for the microwave anti-icing system	96
C.1	Properties of materials used in Study 1. Temperatures are in Kelvin [57]	117
C.2	Properties of materials used in Study 2. Al_2O_3 is the base material and tempera- tures are in Kelvin [74]	117
C.3	Properties of the materials used in Study 3. Al_2O_3 is the base material and tem- peratures are in Kelvin [75]	118
D.1	Mesh comparison between the developed model and Study 1	122
D.2	Mesh comparison between the developed model and Study 2	122

D.3	Mesh comparison between the developed model and Study 3	123
I.1	Properties of the selected microwave absorbing materials	137
L.1	Mesh refinement study for the 3rd Flat Plate Model	144
L.2	Mesh refinement study for the 4th Flat Plate Model	144
L.3	Mesh refinement study for the 5th Flat Plate Model	144
L.4	Mesh refinement study for the MAL Model	144
L.5	Mesh refinement study for the BMI Model	145
L.6	Mesh refinement study for the 2D Airfoil Model with constant convection coefficient	146
L.7	Mesh refinement study for the 2D Airfoil Model with CFD	146
P.1	Wind relative velocity and power required to achieve a 5 °C surface temperature, for each section	156

Chapter 1

Introduction

1.1 Context and Motivation

Energy is indispensable for the existence of life and its continuous production is vital to human existence, progress, and development. As technological advancements have progressed, the capacity for power generation has been required to synchronize with the escalating demands. However, reliance on traditional fossil fuels as main energy sources has led to environmental deterioration and climate change, necessitating a transition towards renewable alternatives. Renewable energy offers the potential to revolutionize global energy systems while mitigating environmental harm and fostering socio-economic development worldwide. In this context, wind energy stands as a particularly relevant alternative, playing an increasingly important role in global energy production, and embodying the principles of sustainability and environmental responsibility.

In order to compete with the conventional energy sources, wind energy production sector is constantly improving its efficiency and capacity. Therefore, wind turbines are increasingly being installed in cold or high-altitude regions, driven by the elevated wind resources and the availability of expansive land. Large-scale wind energy project opportunities are emerging, especially in the high latitudes of Eastern Europe, Asia, and the Nordic region. These regions have an approximately 10% higher kinetic energy available in the wind compared to other areas, attributed to the increased air density in colder temperatures, which means that more mass is moving through a given area. Adding to this, the elevation in these locations enhances wind speeds, creating ideal conditions for wind farm installations [1–3].

However, these locations frequently encounter icing conditions, as shown in Figure 1.1, which present significant challenges for the wind energy production, impacting the assessment phase, transport, installation, operational aspects, and maintenance of wind farms. The accumulation of ice modifies the aerodynamic profile of the blade, increasing drag which results in an immediate impact on the turbines' aerodynamic efficiency. These conditions may also lead to measurement errors (for example in wind speed measurements or ice detection sensors), which can result in incorrect inputs to the control system that could lead to inefficient operation of wind turbines, reduced energy output, and safety risks. These safety issues may also arise as a direct consequence

of ice accumulation on the blades, since the presence of ice will result in increased weight, imbalance and vibrations. The increased loads on the mechanical components may lead to the reduction of the components' lifespan and of the turbine's efficiency. Increased vibrations may also result in elevated noise emissions, and various mechanical failures. Another safety hazard that appears is ice shedding from the blades, that can pose risks to nearby personnel and structures. All the mentioned consequences of ice accretion cause power losses that can reach over 20% of annual energy production, due to efficiency reduction or increased downtime [1, 2, 4, 5].

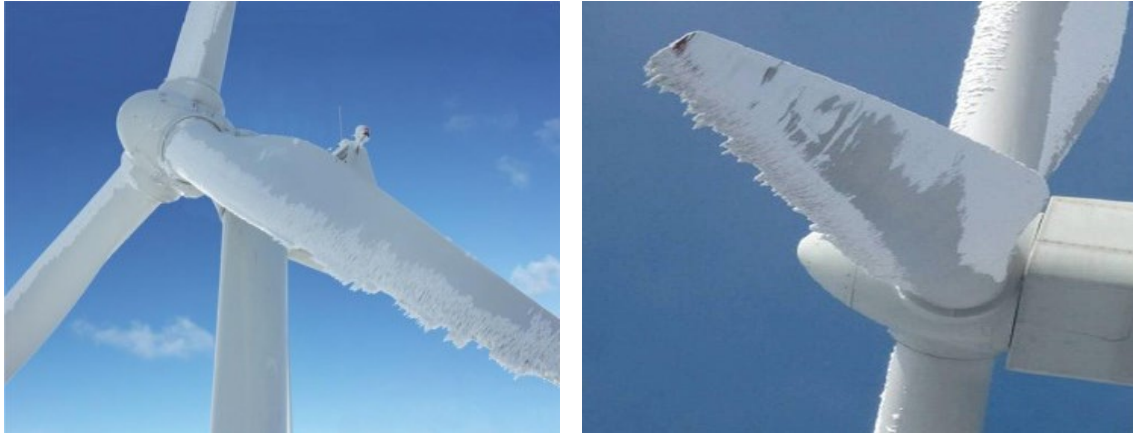


Figure 1.1: Two different examples of ice accumulation on wind turbine blades [4, 6].

The challenges described pose icing as one of the most important factors affecting the operation of wind turbines in cold climates. Consequently, a crucial element in enhancing the efficiency of wind turbines is the use of appropriate, suitable, and effective anti-icing and de-icing equipment. The adoption of ice mitigation strategies and technologies intends to decrease the wind turbine's downtime and increase performance and efficiency, although a business plan that includes the actual costs and advantages of the additional technologies must determine the implementation decision [3, 4].

Given the relevance of these systems in the evolution and improvement of wind turbines' performance in cold climates, new anti-icing and de-icing systems are being developed by companies in this sector, in order to obtain more efficient technologies, with enhanced cost-effectiveness, and easier manufacturing and integration processes.

This thesis, in collaboration with Vestas, studies a potential method of using microwave radiation as an ice mitigation technology, offering an alternative to the current anti-icing and de-icing systems that are being used on wind turbine blades, which will be discussed in subsequent sections.

1.2 Vestas

Vestas Wind Systems A/S stands as a global leader in the wind energy sector, renowned for its pioneering role in wind turbine manufacturing. The Danish company distinguishes itself for having a highly integrated value chain, offering comprehensive solutions ranging from turbine design and

installation to operation, service, and maintenance. Vestas is committed to promote sustainable energy solutions, providing a significant contribution to the growing field of renewable energy [7].

In 1898, a modest blacksmith shop was established in Lem, Denmark, paving the way for what would become Vestas. Initially, the company focused on producing window steel frames, gradually expanding its operations. The 1973 oil crisis motivated Vestas to explore wind energy as a feasible alternative, marking the first notable move towards renewable energy. With support from the Danish government, Vestas produced its inaugural wind turbine in 1979, marking the beginning of its journey in the wind energy sector [7].

By 1985, Vestas encountered a difficult financial situation, which stimulated a restructuring that led to the establishment of Vestas Wind Systems A/S in 1987. Despite this setback, Vestas recognized the potential of wind energy and continued to innovate in the renewable energy sector. In 1995, Vestas developed one of the world's first offshore wind farms, further solidifying its position as a leader in the industry [7].

The company experienced significant growth and expansion emerging as one of the industry leaders in the wind energy sector, with a substantial market share. In a strategic move to consolidate its position, Vestas merged with Danish competitor NEG Micon in 2004, accomplishing a 32% market share and solidifying its status as a leader in modern wind energy [8].

As of 2024, Vestas has installed over 177 GW of wind turbines in 88 countries, being the first company to surpass the 100 GW mark for both turbine installation and service. The implementation of these sustainable energy solutions has resulted in the prevention of 1.9 billion tons of CO_2 emissions, thus playing a significant role in promoting a more sustainable energy ecosystem. According to the Vestas Annual Report of 2023, the company achieved a revenue of 15.4 billion euros and a record-setting 18.4 GW of order intake, in the correspondent period [7, 9].

1.3 Objectives

This dissertation intends to explore and evaluate the feasibility of utilizing microwave energy absorption as an innovative anti-icing technology for wind turbine blades. To achieve this primary goal, the thesis is structured around the following specific objectives:

- Conduct a comprehensive literature review on current anti-icing and de-icing systems, microwave heating mechanisms, microwave energy absorption technologies, and their implementation in ice protection systems for wind turbines and other fields.
- Define and characterize a microwave anti-icing solution, establishing the system's working principle and proposing designs for its integration within a wind turbine blade.
- Investigate potential materials suitable for microwave energy absorption to efficiently convert microwave energy into heat.
- Develop comprehensive numerical models to simulate the microwave anti-icing system by coupling electromagnetic and thermal fields in simplified blade geometries.

- Assess the viability of this technology by analyzing optimal parameters, anti-icing performance, and potential impacts on the wind turbine.
- Compare this preliminary analysis with currently used anti-icing systems, identifying the study's limitations and proposing areas for further research and advancements.

1.4 Structure of the Dissertation

This dissertation is organized into seven chapters, each building upon the previous to comprehensively study the feasibility of a microwave anti-icing system for wind turbine blades. The structure is as follows:

- **Chapter 1: Introduction** - This chapter provides the context and motivation behind the study, introduces the main objectives and outlines the structure of the dissertation.
- **Chapter 2: State of the Art** - This chapter reviews the existing literature on wind turbine technology, ice formation, and the current state of anti-icing and de-icing systems. It also covers the principles of microwave heating and its potential application in anti-icing systems.
- **Chapter 3: Initial Modeling and Validation** - This chapter details the initial development and validation of numerical models using COMSOL Multiphysics. The focus is on modeling the microwave heating process in simplified geometries and conditions, to compare results with the literature and establish a foundation for the study.
- **Chapter 4: Microwave Anti-icing Solution** - This chapter introduces the proposed microwave anti-icing system, detailing the working principle, design options, and material selection for efficient microwave energy absorption and conversion into heat. It also discusses the system's requirements and constraints.
- **Chapter 5: Simplified Microwave Anti-icing System Models** - This chapter expands on the initial models by applying them to simplified blade geometries. It includes the development of four numerical models to study the anti-icing system: two 3D models of a flat plate geometry and two 2D models of a wind turbine blade cross-section.
- **Chapter 6: Discussion of System Viability** - This chapter assesses the viability of the proposed system, examining its performance and efficiency, optimal parameters, potential impacts on the wind turbine, and investment costs estimation. It includes a comparison with existing anti-icing systems and discusses potential design optimizations.
- **Chapter 7: Conclusions** - The final chapter summarizes the key findings of the study, outlines the main conclusions, and suggests areas for future research by addressing the limitations of this investigation.

Chapter 2

State of the Art

In this chapter, it is explored the state of the art within the domain of this thesis, aiming to establish a comprehensive understanding of the theoretical concepts, fundamental knowledge, and contemporary technological advancements that form the backbone of this investigation. Through a systematic review of existing literature and research findings, the composition of wind turbines is addressed, as well as the processes of ice formation, particularly on wind turbine blades. Following that, the current anti-icing and de-icing systems used on wind turbines are briefly described and explained. Furthermore, a theoretical approach to the behavior of microwaves and the process of microwave heating is presented, for a better understanding of this phenomenon. Finally, the current technological landscape of microwave anti-icing and de-icing systems is analysed, to lay the groundwork for subsequent analyses and contributions.

2.1 Background

The theoretical energy available in wind could potentially satisfy global energy needs. However, various constraints such as size limitations of wind turbines, investment costs, insufficient wind velocities, land use concerns, and challenges in grid integration constrain the realizable potential of this technology. Despite these challenges, wind energy presents a sustainable alternative to conventional energy production methods, with economic benefits through its labor-intensive nature, and its competitive leveled cost of electricity at windy locations [10, 11].

The historical use of windmills traces back to the Middle East, thousands of years ago, mainly for water pumping and grain milling purposes. Despite this, only in 1887 occurred the first utilization of wind-generated electricity, when Professor James Blyth erected a turbine featuring a rotor with 10 m. However, following World War I, advancements in large wind turbine technology stagnated for nearly 50 years due to the escalating utilization of fossil fuels. The development of wind energy significantly increased after the oil crisis of 1973, which triggered incentives to the construction and installation of wind turbines, mainly in the USA and in Denmark. The world's first multi-megawatt wind turbine was produced in 1978, by Tvind school in Denmark [12, 13].

For the reasons already mentioned, see section 1.1, cold climate regions have become an important part of wind energy evolution. However, even in the early stages of wind power production, ice accretion revealed to affect the performance of wind turbines in cold climates. Initial efforts to address this problem date back to the 1980s, even though ice mitigation systems were employed firstly in the aircraft industry, a few decades before. Siemens was one of the first companies to develop these technologies for wind turbines, producing its first de-icing system in 1994 [14].

Wind turbines evolved in size, capacity, and number of installations in the last decades. Nowadays, wind energy plays a significant role in the energy sector, with a share of 7.3% of world electricity production and a share of 3.1% in the primary energy consumption, in 2022. In the same year, 77.6 GW of new wind power capacity was connected to power grids, with this value expected to increase to 175 GW by the end of the decade, with the current policies [15–17].

2.2 Wind Turbines

Wind turbines harness the kinetic energy present in wind for energy conversion, particularly for electricity generation. This is achieved by employing blades mounted on a hub/shaft assembly, which captures wind energy and converts it into mechanical energy, transmitting it to the selected energy user (usually a generator). These turbines are essential technologies that have been widely used in the last century to produce renewable energy [10].

There are two primary types of wind turbines: horizontal-axis (HAWT) and vertical-axis (VAWT), with the first being more widespread in today's markets. In HAWTs, the blades rotate around an axis perpendicular to the tower, at the top of it, while in VAWTs they rotate around the tower axis itself. Both types are characterized by parameters such as rotor diameter, number of blades, hub height, rated power, and control strategy [10, 11, 18].

The main components of a wind turbine include the rotor, the nacelle, the tower and the foundation, and are shown in Figure 2.1.

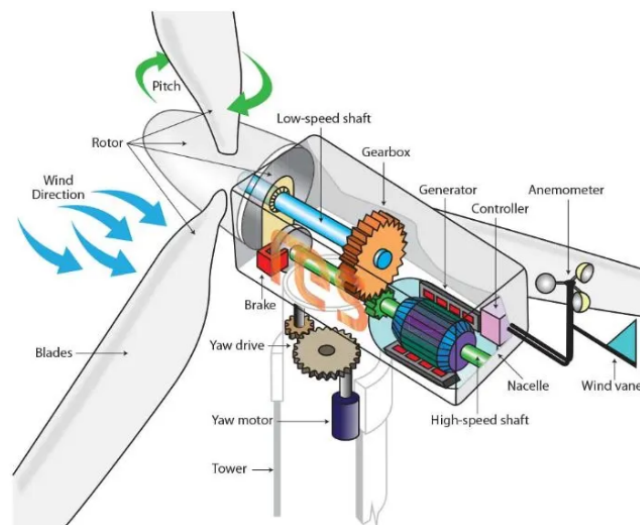


Figure 2.1: Wind turbine components [19].

The rotor, consisting of blades and the hub, serves as the main component for capturing wind energy. These blades, typically three, exploit the kinetic energy of the wind by rotating and transferring mechanical power to the drive train, housed in the nacelle [18].

The nacelle is positioned on top of the tower (Figure 2.1), usually turned to the wind direction during operation, and houses critical components of the wind energy conversion system. It typically accommodates the generator, the drive train, and other essential elements such as measuring devices and electronic components. The drive train encompasses various elements including the low-speed shaft (LSS), bearings, couplings, gearbox, high-speed shaft (HSS), and brakes. Some wind turbines have a direct drive system, without gearbox, but this component facilitates the increase in rotational speeds necessary for electricity generation, by matching the low rotational speed of the rotor shaft (10-50 RPM) with the higher rotational speed required by most generators (1000-3000 RPM), where the extracted mechanical energy is converted into electrical energy [11, 12, 18, 19].

The tower, constructed primarily of steel and/or concrete, provides structural support, nacelle access, and elevates the rotor to capture higher wind speeds, which increase with height. The foundation guarantees solidity in the connection of the structure to the ground and its stability [18].

Furthermore, wind turbines are equipped with yaw and pitch control systems (visible in Figure 2.1), which ensure optimal energy capture efficiency by continuously aligning the rotor and nacelle (yaw) to face the wind direction, and adjusting blade angles (pitch) with changing wind direction and intensity. The control system is also responsible for preventing the generator from exceeding its rated power, the maximum power allowed for the installed generator, particularly at high wind speeds. In cases of wind speed surpassing the cut-out value or when maintenance is required, mechanical, electrical, or hydraulic disc brakes can be employed to stop the rotor efficiently, as well as turning the blades in order to become oriented with the direction of the wind. This last mechanism is also known as "feathering" the blades, where the pitch control system assures that the surface area exposed to the wind is minimized for safety reasons [10, 11, 19].

Blade materials are selected based on factors such as strength, durability, and cost-effectiveness to ensure optimal performance and longevity of the turbine blades. These materials include wood and woven materials, glass fibre reinforced polymer (GFRP), carbon fibre reinforced polymer (CFRP), wood epoxy resins, aluminum, and steel. Currently, blades are predominantly fabricated using GFRP, often combined with varying proportions of balsa, PVC, PET or carbon fibre [12, 18, 19].

The power available in the airflow, upstream of the turbine, denoted as P_{upst} , based on the independent variables ρ_{air} , V_o , and A_s can be defined as [20]:

$$P_{\text{upst}} = \frac{1}{2} \rho_{\text{air}} A_s V_o^3, \quad (2.1)$$

where V_o indicates the wind speed upstream of the rotor, ρ_{air} is the air density, and A_s denotes the swept area where the wind speed is reduced. However, this power is not the maximum achievable

power by a wind turbine. The well-known Betz limit imposes a maximum efficiency, for an ideal wind turbine, of 0.593. This value limits the amount of work that can be converted theoretically from the kinetic energy of an incompressible fluid [20].

Therefore, the expression that represents the power transmitted to the turbine is as follows:

$$P_{\text{turb}} = C_p \cdot \frac{1}{2} \rho_{\text{air}} A_s V_o^3, \quad (2.2)$$

where C_p represents the power coefficient, with maximum theoretical value of 0.593. Notably, this equation highlights that power increases only linearly with density and area (increases with the square of the rotor diameter), and, on the other hand, grows with the cube of the wind speed. Modern optimized wind turbines operate close to the Betz limit, achieving C_p values up to 0.5 [11].

Another important parameter used to evaluate the wind turbine's performance is the capacity factor. This indicator is defined as the ratio between wind turbine's annual energy output and the energy output considering operation at full capacity. On favorable sites, a capacity factor of 30% is expected, possibly rising to approximately 60% [12].

To understand the design of a blade, it is necessary to consider what forces are acting on the wind turbine. Lift and drag constitute the components of the force perpendicular and parallel to the direction of the relative velocity, respectively. Theoretical analysis reveals that using lift rather than drag is significantly more efficient for extracting power from the wind. Consequently, modern wind turbines feature pitchable blades, with a cross-section formed by an airfoil, a streamlined shape characterized by a rounded leading edge and sharp trailing edge, as schematized in Figure 2.2, designed to maximize the lift force imposed by the wind to rotate the rotor, and reduce the drag that can result in undesired loads and reduce efficiency [11, 18].

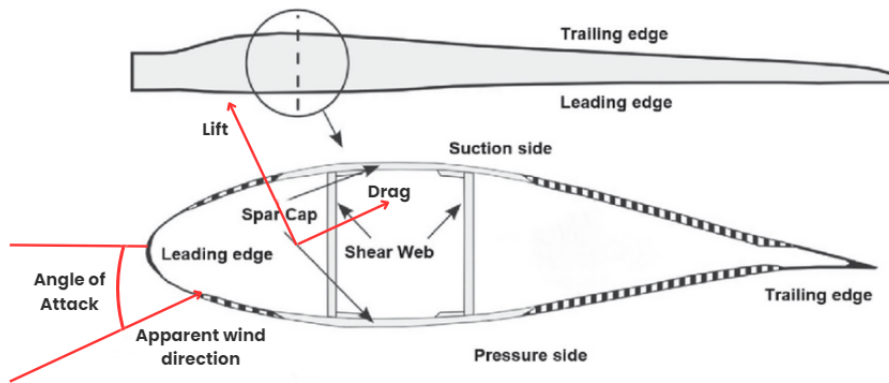


Figure 2.2: Cross-section of a wind turbine blade. Adapted from [21].

The tendency towards larger turbines is one trend accompanying the rapid capacity expansions in wind energy. Over the last decades, turbine sizes, particularly rotor diameters and hub heights, have witnessed significant increases, mostly motivated by reducing the levelized costs of electricity generation. Despite the elevated investment costs, operation and maintenance (O&M) challenges,

and structural considerations, larger turbines offer lower levelized costs of electricity due to higher wind speeds with increased hub height (in line with the cubic relationship of wind speed with wind power), and significantly larger swept areas (power output is proportional to the square of the diameter) with larger rotor diameters. In addition, this increased energy capture efficiency allows for higher electricity generation per unit of land area, helping to conserve valuable land resources and reduce visual impacts on the landscape [18].

Simple aerodynamic and structural enhancements in wind turbines can also lead to marginal improvements in energy production and cost reduction. However, compared to the benefits associated with higher hub heights and rotor diameters, the potential impact of such modifications is low. Remarkably, the tower height of a standard turbine has increased from under 40 m in the 1990s to over 100 m presently, with rotor diameters expanding from 15 m in 1985 to over 160 m today. The largest installed wind turbine (as of April 2024) is Goldwind GWH252-16 MW, located offshore in China, which has a 252-meter diameter, a 146-meter hub height, and a record-setting energy produced in one day of 384.1 MWh [18, 22, 23].

Despite this continuous size increase, modern multi-megawatt wind turbines are not simple upscaled versions of early models, as they integrate advancements enabling their growth without becoming overly heavy or economically unviable. For instance, comparing current Vestas V164-8 MW with V17-75 kW model of 1984, despite increasing almost by a factor of 10 its rotor diameter and a factor of 100 its rated power, the head weight (rotor and nacelle) only increased 80 times that of its predecessor. This impressive improvement in efficiency results from advancements in various domains, including aerodynamics, structures, materials, generator design, control strategy, and power electronics [12].

Vestas current portfolio has onshore alternatives up to 172 meters in rotor diameter and 7.2 MW of power capacity (V172-7.2 MW which had its first firm order in October 2023). Offshore solutions are led by its most powerful turbine, the V236-15.0 MW, with a swept area of 43 742 m² [24, 25].

2.3 Ice formation

The formation of ice on wind turbines is highly dependent on operational conditions such as temperature, humidity and wind speed, as well as on the size of the turbine, since longer blades provide more area for ice to accumulate and, along with taller towers, may expose the turbine to colder temperatures and higher wind speeds. If the surface temperature falls below 0°C while being exposed to supercooled water droplets (water droplets which exist in liquid form at temperatures below 0°C), icing can occur on wind turbine blades [3].

Meteorological conditions closely associated with icing include liquid water content (LWC) of air, air temperature, wind speed, and droplet size (median volume diameter or MVD). The resultant type and shape of ice accumulation are influenced by these atmospheric and meteorological factors, alongside with the surface heat balance. Despite efforts to predict the results of icing under

specific conditions, accurate forecasting is challenged by the complex interaction of atmospheric and climatic factors [3].

The processes of ice formation on wind turbines can be encompassed by the expression "atmospheric icing". There are three principal types of atmospheric icing associated with wind turbines: in-cloud, precipitation-induced, and frost [1, 26].

In-cloud icing forms when supercooled water droplets, with temperatures as low as -30°C , freeze upon contact with a surface below 0°C . The resultant ice accretions vary in size, shape, and properties, influenced by parameters including LWC and MVD of droplets, temperature, wind speed, duration of icing event, and surface area of blades. In-cloud icing includes rime and glaze types, impacted by different meteorological factors and producing distinct ice formations [1–3]:

- Rime ice, the most frequent type of in-cloud icing, forms in freezing fog with supercooled droplets, typically ranging from 0 to $10\text{ }\mu\text{m}$ in size, freezing almost instantaneously on impact. Rime ice usually occurs with high wind speeds, growing in the wind direction, when temperature is between 0°C and -20°C , since the LWC of the air becomes nearly zero at lower temperatures. It lacks crystalline structures and includes air bubbles, appearing as either hard or soft rime, distinguished by density and appearance, and is shown in Figure 2.3 [1–3, 27].

Soft rime occurs when the LWC is low, and the droplet size is small. It is composed of thin white ice (or opaque) with needles and flakes, has low density ($100\text{--}600\text{ kg/m}^3$) and weak adhesion, being easily removed [1–3].

Hard rime is granular, white or translucent, and forms at higher LWC and larger droplets. It has a density of $600\text{--}900\text{ kg/m}^3$ and adheres firmly on a surface which makes it difficult to remove. Wind turbines in high-altitude regions frequently operate in climate conditions that are prone to the formation of hard rime deposits, potentially exceeding 10 cm of height at blade leading edges, posing operational hazards [1–3].



Figure 2.3: Rime ice formation on a wind turbine blade [28].

- Glaze ice is formed by slow freezing of supercooled droplets on objects. This type of ice, shown in Figure 2.4, is hard, compact, transparent, and frequently associated with high LWC and droplet sizes up to $500\text{ }\mu\text{m}$ at temperatures from 0°C to -5°C . It is generally distinguished by the presence of larger protuberances, commonly known as glaze horns. It

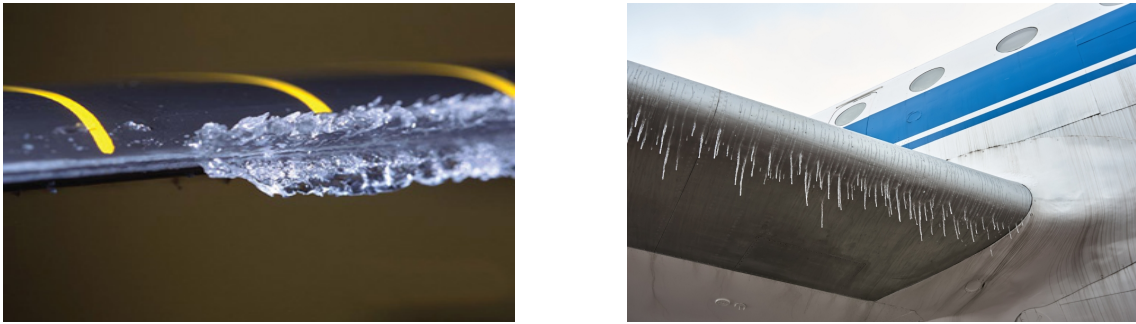


Figure 2.4: Glaze ice on aircraft wings [29, 30].

usually results from wet in-cloud icing, freezing rain or when part of the droplet runs back on the surface and freezes later rather than freezing immediately upon impact. This reduces trapped air, enhances density (close to 900 kg/m^3), and increases adhesion, being difficult to remove. Glaze ice can grow into exceedingly heavy ice loads, posing a danger during operation of the wind turbines [1–3, 27].

Precipitation-induced icing presents serious concerns since it has high accretion rates. The rate of ice accumulation from precipitation substantially exceeds that of water droplets in clouds, leading to increased damage potential. It may result from freezing rain or wet snow [3, 4]:

- Freezing rain occurs when raindrops impact surfaces with temperatures below 0°C . This phenomenon results in high ice density and strong adhesion due to the immediate freezing of rain on the surfaces [1, 3, 4].
- Wet snow forms when slightly liquid snow adheres to surfaces at air temperatures between 0°C and -3°C . Despite being easy to remove at first, it becomes more challenging if it freezes on surfaces. Wet snow accumulation is facilitated by high LWC and temperatures just above freezing, with densities ranging from 200 to 990 kg/m^3 [1, 3, 4].

Frost forms via sublimation of water vapor directly on a surface below 0°C , usually during low wind conditions, temperatures below -8°C and humidity levels typically exceeding 90%. It appears as thin and fragile ice needles or flakes with adhesion that may vary in strength, as presented in Figure 2.5. Frost density is typically less than 900 kg/m^3 and is characterized by its susceptibility to detachment, especially if subjected to windy conditions. Frosting is a common occurrence across wind turbine components, often appearing prominently at blade leading edges. Despite its presence, frost is generally considered to have negligible impacts on wind turbines and their operational loads, only posing safety hazards with several centimeters of thickness [1, 3, 4, 27].

Ice accretion on wind turbine blades is often unevenly distributed (Figure 2.6), accumulating mostly at the leading edge, and frequently with a mixture of different types of icing, as shown in Figure 2.6a. This unequal distribution is influenced by factors such as increasing spanwise relative air velocity along the radius and chord reduction, leading to an approximately linear increase in

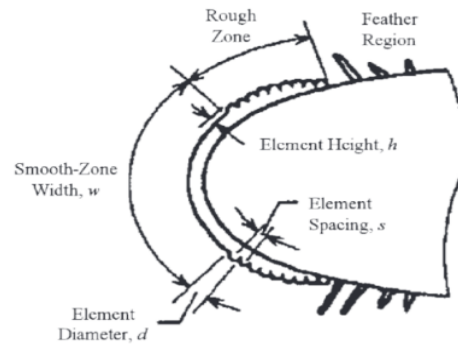


Figure 2.5: Frost formation on an aircraft wing [31].

ice buildup towards the outer part of the blade. Mixed ice accretions may exhibit characteristics of both glaze and rime ice formations. During rotation, the ice at the leading edge of the blade is smoother, and water accumulates on both sides of it, freezing into a rough ice layer, as schematized in Figure 2.6b [3, 4].



(a) Mixed ice formation on an aircraft wing [32].



(b) Ice roughness on a wind turbine blade [4].

Figure 2.6: Ice accretion and distribution.

The presence of ice on blades poses significant safety risks, particularly when detached by centrifugal forces. Ice fragments separated from iced rotor blades have been discovered at distances exceeding 100 meters from wind turbines, highlighting the necessity for adequate safety precautions against ice throw and ice fall hazards [4, 27].

2.4 Anti-icing and De-icing Systems

As already mentioned, ice mitigation systems provide comprehensive solutions adapted to specific needs, effectively addressing the problem of ice accumulation on different objects, since these technologies are not exclusively used on wind turbines. In fact, these techniques are being studied and used for a longer period of time in the aviation industry [1, 2].

Ice mitigation systems employ two primary strategies: anti-icing and de-icing. The former prevents ice accumulation, while the latter eliminates existing ice layers. Both approaches include

passive and active methods. Passive techniques use the inherent physical properties of the surface to either prevent or eliminate ice formation, while active methods require external systems powered by thermal, electrical, chemical, or pneumatic energy sources [1, 2].

2.4.1 Passive Technology

In this section, the anti-icing and de-icing systems using passive technologies (currently available or in development) are enumerated and briefly described.

1. Anti-icing

- **Hydrophobic and ice-phobic coatings**

Ice adhesion on surfaces can be weakened through ice-phobic coatings, that inhibit ice adhesion, like polytetrafluoroethylene (PTFE), polydimethylsiloxane (PDMS), and Wearnlon. Hydrophobic and super-hydrophobic coatings can be used instead, despite being insufficient alone, as they can oppose to water accumulation and, therefore, prevent ice formation [1, 2].

Hydrophobic and ice-phobic coatings are cost-effective, are composed by materials that do not require additional lightning protection, have easy maintenance, and offer overall surface protection. However, studies show that only using these types of coatings are not sufficient to prevent ice accumulation when there are severe icing conditions, since the anti-icing effect disappears when the surface is covered by a thin water film or ice layer. As an alternative, it is beneficial to implement these method with other active anti-icing or de-icing systems, since energy consumption is proved to decrease when a blade heating system is combined with these coatings [1, 4, 33].

- **Black paint**

Black paint can maximize the solar radiation absorption, and for that reason can be used for blade heating. Combined with ice-phobic coating, this method is appropriate where icing is minimal, occasional, and followed by temperatures above 0 °C, or in regions with intense winter solar radiation at lower altitudes. Nevertheless, this technique is frequently unsuccessful in preventing icing, and during the summer, it can cause the blade to overheat, which can increase the temperature of the polymeric matrix affecting mechanical properties of the blade's materials, potentially accelerating creep and fatigue damages. Generally, solar energy is insufficient to prevent icing on the blade surface, especially in regions with low temperatures, high wind speeds, or limited winter solar intensity and duration [1, 2, 26].

- **Chemicals**

Widely employed in aerospace, commercial aircraft, and transportation, chemical anti-icing techniques prevent moisture freezing on blade surfaces. Despite lowering water freezing points, these chemicals are typically pollutants, and require special application and frequent maintenance, limiting their ability to remain on the blades for extended periods [1].

2. De-icing

- **Flexible blades**

Flexible blades are a proposed system that can break ice by bending the blade. This technique theoretically facilitates the removal of ice, although there is limited information about this topic in the literature, and there are safety concerns [1, 4, 33].

- **Active pitching**

Blade pitching can be considered a passive or semi-active method, that aligns iced blades toward the sun by using start and stop cycles, which can be potentially effective in mild icing conditions. However, this approach lacks scientific validation and may represent a risk of damage to wind turbines. Directly orienting blades toward the sun for greater heat energy is appropriate only in minor icing conditions, with unverified and poorly studied impacts on wind turbines lifetime and power production [1, 33].

2.4.2 Active Technology

In this section, the ice mitigation systems using active technologies (currently available or in development) are briefly described. Firstly, the systems used only for de-icing are enumerated. Secondly, all the systems that can be used for anti-icing or de-icing, depending on how they are implemented and controlled, are presented.

1. De-icing

- **Pneumatic methods**

In this system, flexible pneumatic boots inflate on the leading edge of the blade with compressed air to break ice on airfoil surfaces, efficiently shedding ice through centrifugal and gravitational forces. Goodrich company has installed with success this technology in various aircraft, and tested the system on a 1.5 MW wind turbine blade in a laboratory that showed low energy consumption. However, there are still many challenges that need to be addressed, such as its potential aerodynamic disturbance, increased drag, potential ice throw, and noise generation, along with untested field performance. The 20-year operation may demand intensive and expensive maintenance. Although this pneumatic approach is widely used for de-icing in small aircraft wings, its simplicity and energy efficiency can be compromised by changes to the aerodynamics of the blades and a difficult installation process. Figure 2.7 illustrates the principle of the described system [1, 26, 33].

- **Electromagnetic induced vibration**

Electromagnetic impulse de-icing employs rapid electromagnetically induced vibrations to crack ice. Using a controlled discharge circuit connected to a spiral coil close to the profile's surface, this technique creates a magnetic field that produces instantaneous pulse forces which are used to remove ice from aircraft or wind turbine blades.

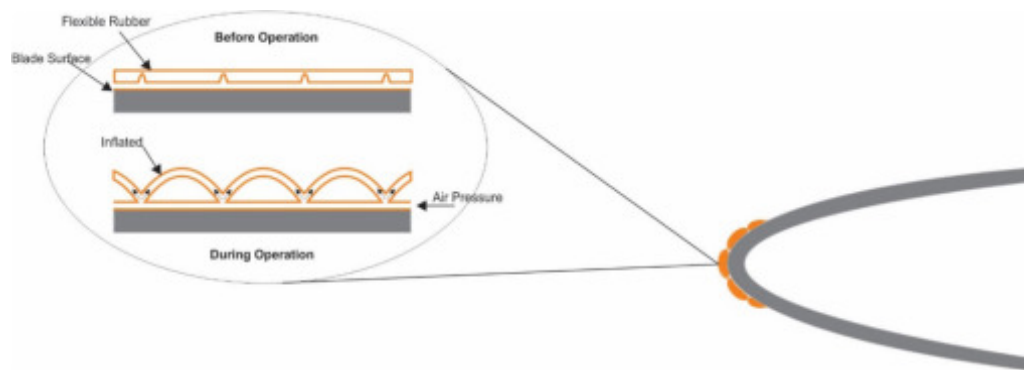


Figure 2.7: The principle of pneumatic de-icing technique, placed on the leading edge of the blade [34].

Through flight and wind tunnel testing, Wichita State University confirmed the viability of this method, confirming high efficiency, low energy consumption, reduced environmental impact, and ease of automation. Despite its successful application in aircraft, its reliability on wind turbines remains untested [1, 33].

- **Ultrasonic de-icing**

Ultrasonic approaches have been extensively studied for aircraft de-icing. They generate shear stresses to separate adhesive layers from the blade surface by directing high-frequency vibrations through piezoelectric actuators coupled to the structure. Ultrasonic wave technology aims to break adhesion bonds between ice and the structure's surface, offering versatile applications with proven efficiency on helicopter blades and promising potential for wind turbines. By employing a lightweight and compact design, with minimal aerodynamic impact, it results in instantaneous and cost-effective de-icing, with low energy consumption. Despite its potential, the technology is not currently being used for de-icing wind turbines, since it requires further investigation and field testing. [4, 26, 33].

2. Anti-icing or de-icing

- **Heating resistance**

Heating resistance is an ice mitigation technology that involves either embedding an electrical heating element inside the blade or coupling it onto the blade's outer surface. These heating devices are positioned on the aerodynamically crucial leading edge of the blade, where ice formation is most substantial, and are typically thermal pads, electrically heated foils, and metal or carbon fiber elements. Power connections are located at the root end of the blade [1, 2, 26].

Heating resistance operates in two modes: anti-icing to maintain the blade temperature above 0 °C, activated upon detecting conditions that stimulate ice formation; and de-icing, triggered by an ice-detecting device. In de-icing mode, the heating element generates heat

upon detecting ice, creating a water film between the ice and the blade. The ice is then removed by the centrifugal force of the blade, preventing accumulation [4, 33].

In de-icing, when the ice cleaning concludes, if the temperature sensor detects that the temperature is too high, a signal is given to turn off the heating element in time to avoid damaging the blade due to excessive high temperatures [4].

The thermal energy required to de-ice is greater at the blade tips than near the hub due to more severe icing conditions caused by increased airflow. A greater sweep area that collects more ice, proximity to low clouds, and a greater relative velocity at the tips that speeds up ice accretion are some of the contributing factors. To address this, the technology frequently allows individual powering of heating elements, ensuring equal power distribution where required along the blade. Vestas Anti-icing system is based on this technology, with electro-thermal heating elements embedded in the laminate directly underneath the blade's surface to provide rapid and precise heating response, as shown in Figure 2.8. The system is activated automatically when detected degradation in turbine performance and based on environmental conditions [34, 35].

These methods, employed in aerospace for many years and in wind industry since the 1990s, offer close to 100% thermal efficiency (conversion of electrical energy into useful heat). However, in severe icing cases, heating power could be insufficient, and challenges emerge over increased lightning risks due to the presence of conductive elements, complex manufacturing, and substantial electrical power requirements. Furthermore, the aerodynamically harmful effect of the icing of runback water on the blade's unheated sections can lead to inefficient de-icing. In extreme icing events additional risks of ice throw may arise [1, 2, 4].



Figure 2.8: Schematic of Vestas' heating resistance anti-icing system [36].

- **Hot air injection**

Hot circulating air technology involves blowing warm air into the blades to indirectly heat the blade surface, and either prevent ice formation (anti-icing) or remove accumulated ice

(de-icing). Using an air closed circuit, it divides the blade's internal volume into two sections, injecting hot air into one part and returning cold air to the heating system in the other section. In de-icing, the surface heating creates a water film between ice and the blade, allowing centrifugal and gravitational forces to remove the ice [1, 2].

This method, which is widely used in aviation anti-icing, was first used to wind turbines in 2009 by ENERCON and more recently by Senvion and Vestas. ENERCON's hot air injection system is shown in Figure 2.9. The primary distinction is that, in contrast to aircraft where the fan is often positioned in the center of the wing, wind turbines have an electrical fan that is normally located at the root of the blade and requires hot air to be driven a great distance [26].

Effective in milder climates where icing occurs close to 0 °C, hot air injection does not require additional lightning protection. Aerodynamic aspects remain unchanged since all components are in the blade root, and the air flow is internal. However, it consumes significant power at high wind speeds and low temperatures, with effectiveness dependent on meteorological conditions and blade size. Low thermal efficiency (around 30%) is the primary problem, which is explained by the necessity to heat a large mass before reaching the blade surface. Additionally, the heat source, often a hot air blower, locates typically at the blade root while the highest heat fluxes are required at the blade tip. Efficiency can be further increased by utilizing waste heat from machinery. In de-icing mode, there is also a safety hazard related to ice projection [1, 2, 26].

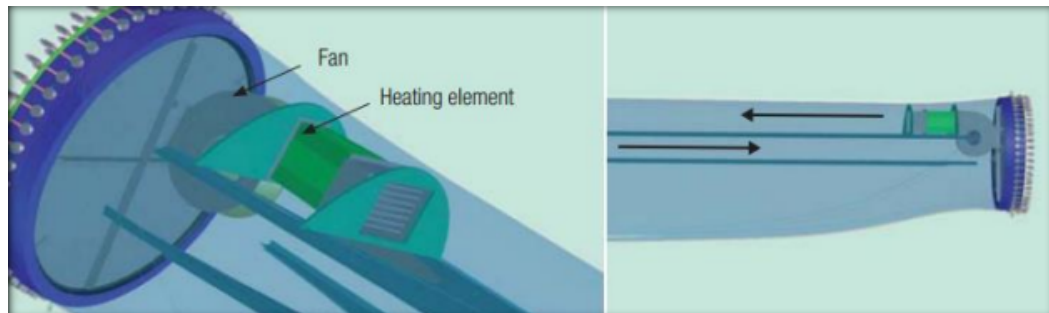


Figure 2.9: Hot circulating air technology from ENERCON [37].

- **Air layer**

Air layer technology involves channeling airflow from inside the blade through small holes near the leading and trailing edges to create a clean and, if needed, heated air layer around the blade surface, as shown in Figure 2.10. This technique can act as an anti-icing device, where most water droplets are successfully deflected, and also melts any that come into touch. In severe icing conditions, it could work on de-icing mode, heating the surface of the blade to remove the ice accumulated. Limited published information is available on this

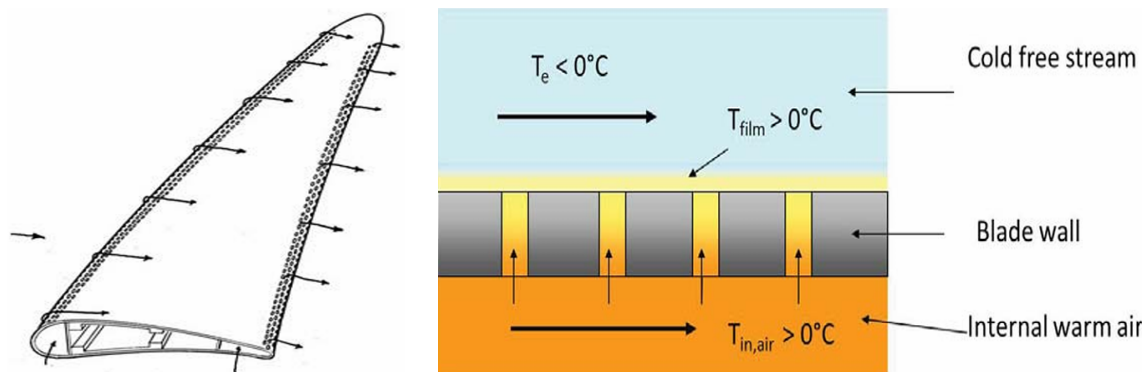


Figure 2.10: Air layer configuration and heat transfer mechanism [3].

method, and it is possible that the airflow will affect the blade's aerodynamic properties [1, 4].

- **Infrared heating**

Infrared heating devices deliver energy to a distant object without requiring installations on the blades, placing the infrared heaters at the wind turbine tower. Suitable for de-icing or anti-icing, it melts and sheds ice through heat absorption. However, careful material selection is important as ice strongly absorbs infrared radiation, which can result in safety risks. For example, polished aluminum absorbs only 10%, while oils absorb 90%, posing a risk of overheating for lubricants and nacelle components. Given the mentioned reasons, special safety measures are necessary for this technology. It has been tested in small-scale in laboratory, by Luleå University of Technology, managing to de-ice a blade section, but with low efficiency compared to the commercially available systems [26, 38].

- **Microwave radiation**

This method consists in using microwave energy absorption to prevent ice formation or to remove accumulated ice. Analysing the viability of this approach is the purpose of this dissertation and, therefore, it will be further described in the next sections.

2.5 Microwaves

Microwaves are electromagnetic waves that correspond to a specific part of the electromagnetic spectrum, which represents the entire distribution of electromagnetic radiation according to frequency, wavelength, or photon energies [39].

Microwaves are commonly classified within a specific frequency range, although there are variations, highlighting the absence of a specific physical phenomenon defining a precise frequency boundary. According to most textbooks, microwaves correspond to frequencies between 300 MHz and 300 GHz, corresponding to wavelengths between 1 m and 1 mm, as visible in Figure 2.11. Alternatively, 500 MHz or 1 GHz are suggested as a lower limit by certain authors. The

frequency range of 30 to 300 GHz, which reflects wavelengths between 10 and 1 mm, is often referred to as millimeter waves [39–41].

While first explored by Hertz in 1886, practical applications awaited the invention of suitable generators. Microwaves are vital for high-speed data transmissions among Earth stations, satellites, and space probes, and they are becoming increasingly relevant in food heating, cooking, imaging, remote sensing, industrial heating, medical applications, and many other physical and chemical fields in recent years [39].

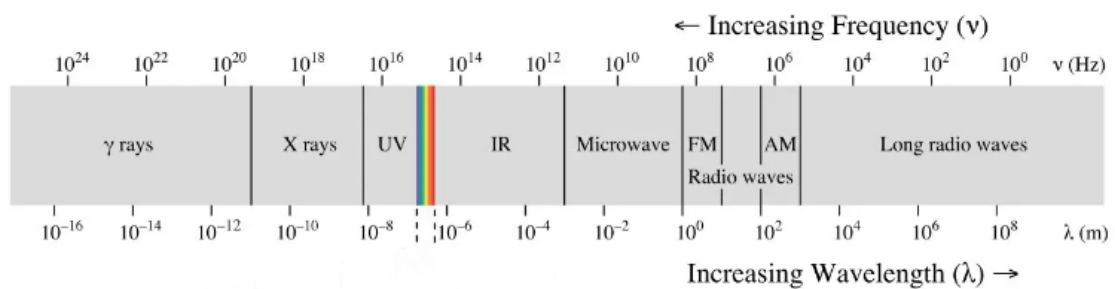


Figure 2.11: Microwaves in the electromagnetic spectrum [42].

2.5.1 Microwave Propagation

The microwave regime involves wavelengths comparable to the dimensions of objects in the electromagnetic field, giving rise to non-intuitive effects. Devices operating at microwave frequencies require specialized knowledge, as phenomena such as wave diffraction are strongly correlated to the ratio between the wavelength and the obstacle dimension. Microwaves' range of frequencies require particular consideration in terms of transmission. High-frequency optical or low-frequency radio transmission concepts face challenges at microwave frequencies, leading to the use of waveguides for effective transmission. These structures are designed to confine and direct the electromagnetic waves, and the propagation of energy is essentially a reflection phenomenon. There are also surface waveguides that guide and confine electromagnetic waves along their surfaces rather than within a major structure [40, 43].

Microwave propagation in the atmosphere is influenced by factors like temperature, humidity, pressure, and composition. These atmospheric conditions cause the signals to be scattered, refracted, and attenuated, which affects signal transmission. Microwaves can penetrate clouds of smoke but are scattered by water droplets, and atmospheric gases such as oxygen and water vapor can absorb microwave energy, leading to signal attenuation. Understanding these effects is essential for enhancing the efficiency of diverse applications, including microwave heating technology [39, 44].

2.5.2 Microwave Absorption

Microwave absorption theory states that incident power on absorbing materials leads to reflection, absorption, and transmission of electromagnetic waves. Microwave energy is converted to thermal energy through interaction with the molecular and electrical structures of the material, leading to energy absorption. [45, 46].

The dispersive effect within materials, generating multiple internal reflections, enables the transmitted electromagnetic waves to expand their propagation path, as it is shown in Figure 2.12, enhancing absorption potential.

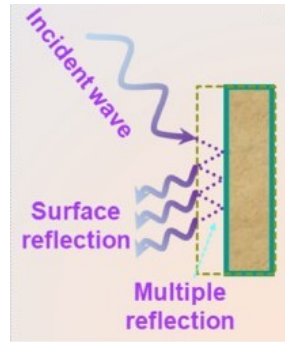


Figure 2.12: Reflection process between an electromagnetic wave and an absorber [47].

It is well-established that the absorbing material reduces the quantity of reflected microwaves by absorbing electromagnetic waves as the signals propagate through it. The absorption of microwave materials is dependent on a variety of factors, including the impedance matching of the absorbent material with the free space, the specific resistance of the material, the frequency, the flexibility of the material to operate across different frequency ranges, and the loss mechanisms [45].

Microwave absorbers are presented with two main loss mechanisms: magnetic loss, that represents the magnetic interaction between the electromagnetic wave and the material; and dielectric loss, which represents the feature of electrical interaction between the material and the electric field of the incident electromagnetic radiation. For nonmagnetic dielectrics, the absorption of microwaves is related to the permittivity (ϵ), while for magnetic materials, the absorption of microwaves depends on both the permittivity and permeability (μ) [46].

Permittivity can be defined as follows:

$$\epsilon = \epsilon_0 \epsilon_r = \epsilon_0 (\epsilon'_r - j\epsilon''_r), \quad (2.3)$$

where ϵ_0 is the permittivity of free space (8.854×10^{-12} F/m), j is the imaginary unit ($j^2 = -1$), and ϵ_r is the complex relative permittivity. ϵ_r can be divided into two components: the real part of complex relative permittivity or the relative dielectric constant (ϵ'_r), that is a measure of the ability of the dielectrics to store electrical energy, and the imaginary part of complex relative permittivity or the relative dielectric loss factor (ϵ''_r), that represents the loss of electrical energy in dielectrics. This loss capability mainly comes from conduction loss and polarization loss [46, 47].

Permeability is defined by the following equation:

$$\mu = \mu_0 \mu_r = \mu_0 (\mu_r' - j\mu_r''), \quad (2.4)$$

where μ_0 is the permeability of free space ($4\pi \times 10^{-7} \text{ H m}^{-1}$), and μ_r is the complex relative permeability. It is used to describe the constitutive relation between the magnetic flux density and the magnetic field intensity where the magnetic field-based loss mechanisms exist. μ_r is also divided into two components: the real part of complex relative permeability or the relative magnetic constant (μ_r'), that is a measure of the ability of the materials to store magnetic energy, and the imaginary part of complex relative permeability or the relative magnetic loss factor (μ_r''), that represents the loss of magnetic field energy. This last-mentioned loss can be caused by eddy currents, magnetic resonance and magnetic hysteresis. [46, 48].

Since the energy lost from the electric and the magnetic field is converted into heat when microwave energy is applied, ϵ_r'' determines the heating rate in dielectrics without magnetic properties, and μ_r'' is determinant in the heating rate of magnetic materials. It must be stated that both permittivity and permeability can change with frequency and with temperature, resulting in an increased difficulty when modeling accurately microwave systems.

The efficiency of converting microwave energy into thermal energy of a material is often expressed by the loss tangent ($\tan \delta$). The higher the loss tangent of the material, the stronger the ability of converting microwave energy into heat. For nonmagnetic materials, $\tan \delta_\epsilon$ is defined as the ratio of the imaginary to real parts of permittivity (Equation 2.5). In magnetic materials, $\tan \delta_\mu$ is similarly defined for permeability, as it is presented in Equation 2.6. Some materials can have both types of losses, and, therefore, will depend on both this parameters [46, 47].

$$\tan \delta_\epsilon = \epsilon_r'' / \epsilon_r', \quad (2.5)$$

$$\tan \delta_\mu = \mu_r'' / \mu_r'. \quad (2.6)$$

2.6 Microwave Heating

Microwave heating is an innovative alternative to conventional heating methods, offering a different approach which employs an energy conversion process from electromagnetic energy to thermal energy, instead of a heat transfer process. In contrast to the conventional method of heating, which involves heat conduction from the material's exterior to its inside, microwaves are able to penetrate materials and deliver energy, which causes internal heat generation and, as a result, volumetric heating. Consequently, the thermal gradients and flow of heat are the reverse of those in materials heated by conventional technologies, with the energy being provided directly through molecular interaction with the electromagnetic field, and significantly enhancing the heat transfer to the interior of the material [46, 49, 50].

The advantages of microwave heating, in comparison to conventional methods, are noteworthy. This method exhibits a versatile penetration depth, ranging from meters to millimeters, which allows for the avoidance of large surface temperature gradients in appropriately sized materials under microwave irradiation, favoring uniform and rapid heating. In addition, this approach has the potential to save energy and time, allow the possibility of selective heating, significantly reduce processing time and have low environmental impact [46].

As previously mentioned, microwave heating involves the conversion of electromagnetic energy to thermal energy through two primary loss mechanisms: dielectric heating and magnetic field-induced heating.

Dielectric heating includes two main phenomena: dipolar polarization, known as polarization loss, and ionic conduction, or conduction loss:

- In the polarization mechanism, dipoles attempt to align themselves by rotating in response to external electric fields. However, at high frequencies, the rapid oscillation of the electric field prevents dipoles from aligning in time, leading to collisions and the dissipation of power, which results in heat generation in polar materials like water. This dipolar polarization mechanism is central to microwave dielectric heating, particularly in electrically insulating materials [46, 50].
- Under the influence of the microwave electric field, mobile charge carriers, such as electrons or ions, flow back and forth across the material in the conduction process, producing an electric current. These induced currents generate conduction loss due to Joule effect caused by collisions between charged species and nearby molecules or atoms, generating heat. [50].

With the consideration of dipolar polarization and ionic conduction, the relative dielectric loss factor (ϵ_r'') for the dielectric heating expression can be presented as [50]:

$$\epsilon_r'' = \epsilon_p'' + \epsilon_c'' \quad (2.7)$$

where ϵ_p'' and ϵ_c'' represent the polarization and the conduction contributions to the imaginary part of relative permittivity, respectively.

Polarization loss can be defined according to Debye's theory as [48]:

$$\epsilon_p'' = (\epsilon_s - \epsilon_\infty) \frac{\omega\tau}{1 + \omega^2\tau^2}, \quad (2.8)$$

and conduction loss is described by the following expression [46]:

$$\epsilon_c'' = \frac{\sigma}{\epsilon_0\omega}, \quad (2.9)$$

where ϵ_s , ϵ_∞ and τ represent the permittivity at a frequency approaching zero and infinity, and relaxation time, respectively. σ represents the electrical conductivity of a material, and ω denotes the microwave angular frequency and is defined as:

$$\omega = 2\pi f, \quad (2.10)$$

where f is the microwave frequency.

Expanding on the magnetic loss mechanisms, microwave magnetic field heating involves some major processes, as previously stated, including eddy currents, magnetic hysteresis loss, and magnetic resonance loss:

- Eddy current loss results from Joule heating caused by the eddy current induced due to the interaction between a conductive material and an alternating magnetic field [50].
- Hysteresis loss occurs exclusively in magnetic materials, and it is caused by the irreversible magnetization process within an alternating magnetic field. As magnetic materials experience changes in their magnetic poles every cycle, the magnetic dipoles oscillate, leading to significant friction and internal heating [50].
- Magnetic resonance losses are also important contributors to microwave heating, particularly in metal oxides like ferrites and other magnetic materials. These losses are mainly induced by domain wall resonance and electron spin resonance. Essentially and in simple terms, the microwave-induced oscillations at the domain walls (interfaces between regions in the material where the magnetization has different directions), and the spinning of electrons contribute to the overall heating effect in these materials [46, 50].

The relative magnetic loss factor (μ_r'') can be expressed in terms of the three main loss mechanisms:

$$\mu_r'' = \mu_{\text{hysteresis}}'' + \mu_{\text{eddy current}}'' + \mu_{\text{resonance}}'' \quad (2.11)$$

The efficiency of microwave heating is affected by factors such as power, frequency, radiation time, applicator design, sample absorption properties, and dimensions. Efficient microwave heating depends significantly on the propagation and dissipation of microwaves within materials, described by Maxwell's equations and corresponding boundary conditions, hence maximizing microwave energy absorption is crucial for enhancing heating efficiency. Furthermore, efficient heat transfer during the process is similarly essential to the effectiveness of microwave heating as heat generation within the absorber [46]. These concepts are further detailed in Appendix A, where a summarized presentation is made of the set of physical equations used in this dissertation.

2.6.1 Microwaves Generators

Microwave heating technology has evolved through various types of generators, with vacuum-tube devices, namely the klystron and magnetron, being widely utilized, which are particularly useful in high-power applications. Klystrons mostly serve as amplifiers in radio relay systems and for dielectric heating, whereas magnetrons have found applications in radar systems and microwave

ovens. These devices have been essential since the 1940s and remain prevalent, but recent developments are shifting the landscape towards solid-state microwave generators [39, 51, 52].

A klystron, a vacuum tube, converts high-voltage pulses from a pulse modulator into high-power microwaves [53]. In contrast, a magnetron generates microwaves through the interaction of electrons and resonant cavities. It is composed by a cylindrical anode block with resonant cavities, a central cathode, and two strong permanent magnets, as it is shown in Figure 2.13. The central cathode is a heated filament that releases electrons, while the magnets produce a strong magnetic field around the device. When the cathode is heated, it emits electrons that are forced to move in a spiral or circle path towards the anode by the magnetic field. As the electrons move, they induce an oscillating electric field within the resonant cavities of the anode block, which creates standing waves and ultimately generates microwaves. These are guided out of the magnetron through an antenna or waveguide. Despite their historical significance and proved reliability, magnetrons pose limitations such as a limited lifespan, difficulty in troubleshooting, and service complexities [54].

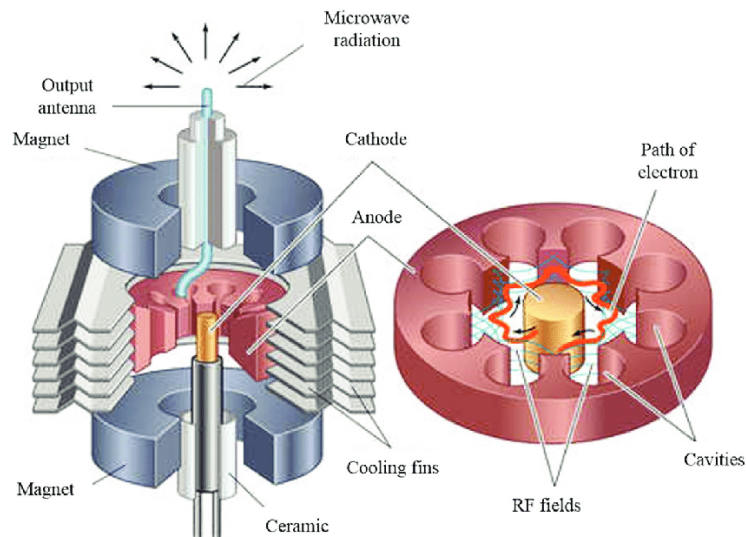


Figure 2.13: Magnetron schematic for generation of microwave radiation. [55].

This dominance of magnetrons is being challenged by the emergence of solid-state microwave generators, that can overcome some of the limitations mentioned above. Magnetron tubes have a lifetime of only a few thousand hours (between 5 thousand and 10 thousand hours), while solid-state systems offer extended lifespans exceeding 30 years. This technology also enables precise frequency control, and enhanced power regulation. Unlike magnetrons, they operate at lower voltages, simplifying design and ensuring safety, and can also obtain a power of several kilowatts, combining several semiconductor amplifiers until the desired power is acquired. In addition, solid-state generators provide finer frequency control, enabling swift power adjustments and maintaining output power without degradation, as opposed to the capabilities of magnetrons, where the emitted frequency cannot be chosen within a narrow bandwidth as it fluctuates slightly. This variance in microwave frequencies makes it particularly challenging to predict and control locations of cold and hot spots, when using magnetrons. Nevertheless, the shift to solid-state technology faces

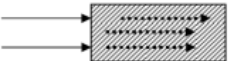
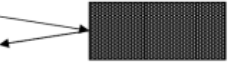
challenges related to costs, knowledge gaps, and active cooling requirements [52, 56].

In summary, the transition from magnetrons to solid-state microwave generators reflects a technological shift motivated by increased control capabilities, reliability, and enhanced efficiency. While magnetrons have been fundamental in microwave applications and are highly efficient in converting electric power into microwave energy, the rise of solid-state technology signals a promising future, especially in addressing issues of non-uniform heating and providing more flexible and controlled microwave energy delivery [51, 56].

2.6.2 Microwaves Absorbers

Regarding microwave applications, there are three main groups of materials: transparent, absorbers and reflectors. Transparent materials do not have significant dielectric or magnetic losses, therefore, the incoming incident microwaves propagate inside the material without considerable attenuation, resulting in negligible heat generation. In contrast, absorbers are materials with high dielectric and/or magnetic losses, which result in high attenuation of microwaves and further conversion into heat. Materials with extremely high attenuation, such as metallic materials, will act as reflectors because of their high values of electrical conductivity, which do not allow for microwave penetration into the material. This information is summarized in Table 2.1 [46, 57].

Table 2.1: Materials classification in microwave heating. Adapted from [46]

	Material Type	Penetration
	TRANSPARENT (no heat)	Total transmission
	ABSORBER (materials are heated)	Partial to total absorption
	REFLECTOR (no heat)	None

Microwave-absorbing materials are applied on aircraft, ships, and structural parts to minimize scattered electromagnetic wave power. They can also be used to improve the microwave heating efficiency, by acting as a transducer to convert electromagnetic energy into heat. There is a diverse range of microwave materials, each with optimal absorption properties within specific frequency ranges. Effective absorption relies on two fundamental parameters: reduced reflection of incoming microwaves and efficient attenuation of transmitted microwaves [45, 48].

As previously discussed, microwave absorbers usually exhibit noticeable dielectric and/or magnetic losses. The degree of impedance matching between the absorbing material and the free-space is, as mentioned in Section 2.5.2, fundamental to define the absorption capacities of a material, for a given frequency and thickness. This parameter is further detailed in Section A.3.1. For microwave heating applications, the desired characteristics of microwave absorbing materials, besides a strong microwave absorption, include: broad absorption bandwidths, low density, small

thickness, good resistance and durability, low-cost, and advantageous thermal properties, such as significant thermal conductivity and enhanced heat resistance [45, 46].

Introducing magnetic absorbers into coatings effectively reduces coating thickness, because these provide higher loss efficiency per unit thickness, compared to dielectric materials. Nevertheless, achieving impedance matching often requires a combination of dielectric and magnetic materials, leading to the widespread use of dielectric-magnetic composite absorbers. These absorbers can be divided into two categories: resonant absorbers and broadband absorbers. Resonant absorbers involve materials interacting resonantly with incident radiation at a particular frequency. In contrast, broadband absorbers utilize materials almost independent of frequency, allowing them to absorb electromagnetic waves over a broad bandwidth [48, 58].

Currently, microwave absorbers are mainly being designed with composites. Matrix and filler are the two basic components, where the filler is the absorbing material and is dispersed in the matrix material. The selection of an appropriate matrix for microwave absorbers is contingent upon various factors including electrical performance, mechanical properties, thermal properties, outdoor resistance, and durability. Given this characteristics, elastomers, resins and foams are the most widely used matrix materials for microwave absorption applications [59].

Microwave absorbing materials (fillers) are mainly magnetic materials (magnetic metals, alloys, and oxides), and carbon-based materials (carbon nanotubes, graphene, silicon carbide, and carbon fiber). Other nanomaterials with unique structures, metamaterials and frequency-selective surfaces have also been developed to enhance electromagnetic absorption. Highlighting some of these materials, a brief description of suitable absorbers is presented [45, 47]:

- Ferrites are ferro-magnetic materials, which possess high permeability and mild permittivity in the decimeter to millimeter frequency range, making them useful in microwave systems that require a strong coupling to electromagnetic signals and non-reciprocal behavior [45, 47].
- The magnetic loss-dominated microwave absorption materials often include materials with high permeability, including magnetic alloys and magnetic metal oxides. Alloys are frequently used as electromagnetic wave absorbers due to their strong magnetic loss ability and increased saturation magnetization. In the GHz frequency band, they lose electromagnetic waves mostly through natural resonance and eddy current loss [48].
- Carbon-based nanomaterials, such as porous carbon, carbon nanotubes (CNTs), graphene, and carbon fibers, exhibit excellent microwave absorption properties because of their superior dielectric characteristics and rational structural design. However, since carbon-based nanomaterials have a low magnetic loss, effective impedance matching is challenging. Therefore, achieving remarkable electromagnetic wave absorption efficiency for these materials remains difficult. Recent reports highlight efforts to combine magnetic and carbon-based materials through physical or chemical approaches, in order to achieve good impedance matching [45, 47].

- Metamaterials are materials with unique artificial structures that exhibit unnatural magnetic and electric properties. Their special design with a unified array structure is primarily responsible for these qualities, which enables exceptional microwave absorption capabilities, as it can manage efficient permittivity and permeability. Fundamentally, metamaterials increase absorption by reducing electromagnetic wave reflection through improved impedance matching between materials and free space. This is accomplished by stimulating electric and magnetic resonance between the arrayed units in the structure [48].

2.7 Microwave Anti-icing and De-icing

After understanding the basic principles of microwaves, their propagation and absorption, how they could be used as a heating source, and what type of existing generators and absorbers are currently studied and implemented, the next section looks at how microwave technology can be implemented as an anti-icing or de-icing system.

As already mentioned in Section 2.4, this approach consists in the prevention of ice formation (anti-icing system) or in ice removal (de-icing system) by using microwave energy absorption.

2.7.1 Concept

Similarly to the majority of the mentioned anti-icing and de-icing systems in Section 2.4, the initial stages of using microwave technology for this purpose can be traced back to its origins in the aircraft industry. When it was introduced to the wind energy sector, opinions regarding its efficiency diverged, leading to a variety of perspectives. Over the years, various methodologies have been considered to harness its potential. The fundamental premise centers around a system that employs microwave radiation to generate thermal energy. This thermal energy is subsequently used to elevate the temperature of wind turbine blades, ensuring that their surfaces remain above 0°C. The overall objective is to prevent the formation of ice or facilitate the removal of accumulated ice, thereby improving operational efficiency in cold climatic conditions. This system has the potential to enable excellent heat distribution, reduce heating time, and be more cost-effective than traditional methods. Theoretically, it is easy to install and maintain, is not subject to lightning, and does not require significant modifications to the blade structure. It has not yet been successfully implemented by wind energy companies as a replacement for conventional heating systems, despite its potential [1, 2, 26, 60].

Efficient utilization of microwaves for direct heating of accumulated ice is restricted by the ice limited microwave absorption characteristics. Ice exhibits a relative dielectric constant of 3.2, coupled with a small loss angle constant value of 0.0009. Consequently, the power loss of microwaves in ice is negligible, which makes the ice layer nearly transparent to microwaves. As a result, the direct transmission of microwave energy is considered impractical due to its inefficiency, leading to a focus on heating the blade surface as the preferred application for this method [61].

The implementation of this technology can have various and different designs, but the approaches are based on the same principles. One or more microwave generators are installed either

inside the blades, inside the hub, or on the exterior. The electromagnetic energy is transmitted by antennas or waveguides, and is absorbed by specific transducers, such as microwave absorbing materials, where it is efficiently converted into heat. However, further risks need to be considered when selecting an absorber, as any material that includes conductive materials, such as carbon for example, imposes a risk in lightning protection.

Microwave generators, as described in Section 2.6.1, can either be magnetrons or solid-state generators. Independently of the type of generator, strategic placement at various points along the blade enhances energy distribution. The activation of these generators can be independent, allowing for tailored responses to specific requirements. To reduce the number of cables in the blade, the multiple microwave generators can be placed at the root of the blade, or in the hub, with waveguides facilitating energy distribution towards the blade tip [60].

Placing the generator in the exterior of the blades has also been studied and contemplated. However, substantial energy loss occurs when microwaves are transmitted through the atmospheric air, as detailed in Section 2.5.1. There are also challenges associated with directing the transmitted microwaves only to the iced surfaces. In addition, reflections of microwave energy from the surface to be de-iced result in further inefficiency. In contrast, positioning one or more microwave generators on the interior allows for efficient conversion of microwave energy into thermal energy, that can then propagate through thermal conduction to reach the blade skin surface [3].

2.7.2 Current State of the Art Overview

As mentioned, there are several possible configurations to implement this method, with different innovations, theoretical formulations, and experimental tests being developed in the last decades. This section encompasses the presentation of these research initiatives and studies.

- Microwave ice prevention systems' first patent dates back to 1982, when Robert J. Hansman proposed a method which was specifically designed to prevent ice formation on the leading edge of aircraft wings, using a surface waveguide dielectric coating to distribute the microwave electromagnetic energy in the heating region [62].

The procedural framework of this innovative approach included several steps. Initially, microwave electromagnetic energy is generated, followed by its transmission to the heating region situated on the leading edge of the wing. The distribution of this energy ensures that any incident supercooled water droplets are heated by absorption of microwave energy sufficiently to prevent ice formation. Instead of the surface waveguide, microwave antennas could be used to perform the distribution of the microwave energy in the heating region, as illustrated in Figure 2.14, where the antennas are represented by components 35. The microwave tube employed is a conventional oscillator, such as a magnetron or a klystron. The selection of the microwave frequency is as a crucial design parameter and is chosen according to the absorption properties of liquid water. As a result, the designated frequency would typically fall within the range of 2 to 24 GHz [62].

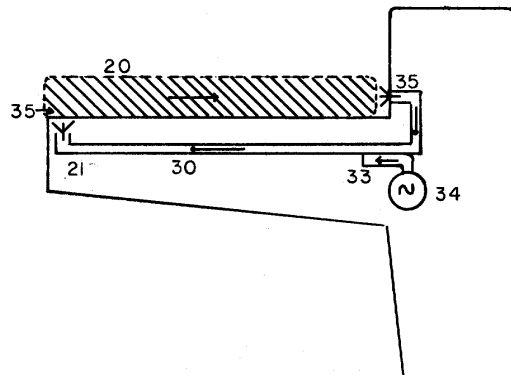


Figure 2.14: Schematic of the ice prevention system proposed by Robert J. Hansman (20 - heating region; 21 - wing; 33 - directional coupler; 34 - oscillator; 35 - antennas) [62].

- In 1998, another patent was filed regarding these type of systems by the Danish company LM Glasfiber (currently LM Wind Power). Microwave energy is used to heat the composite material of the blade, to avoid icing on its surface. This energy is preferably supplied from internally mounted microwave generators, triggered by detecting potential icing conditions. The wing surface can be coated with a microwave-reflecting layer, allowing the energy to be supplied from the inside and propagate through reflections within the shell parts of the blade. Selective heating can be achieved using multiple generators, which may be magnetrons provided along the front edge of the blade, or in its root coupled with waveguides for energy distribution as presented in Figure 2.15. In this Figure, component 2 represents the blade, while 6 and 7 represent the microwave generators and the horn antennas that transmit the electromagnetic waves, respectively [63].

The company developed and tested a microwave system in small scale on a LM19.1 blade. A microwave generator at 2.45 GHz and a power emission of less than 10 mW/m^2 were used in these tests. The power unit had a minimal impact on blade costs and did not reveal any lightning issues. However, it was concluded that further tests with higher power were required due to the low energy absorption obtained in the ice [1–3].

- In 2002, Lambert Feher patented an invention to employ a compact microwave de-icing system for hollow or shell body structures which are subject to the formation of ice, such as wind turbine blades. It features independently operable microwave generators situated in each shell structure, adjacent to the surfaces requiring de-icing (or heating to prevent icing). The mechanically robust shell bodies are made of carbon or glass fibers and possess an outer surface with a metallic film or skin, as schematized in Figure 2.16. The microwave source is placed directly at the action area, eliminating the need for long guide structures or waveguides. Along the heated area, uncoupling apertures direct a microwave front toward the surface. This wavefront penetrates the wall of a dielectric composite material with a metallic skin, generating heat within the composite material. Another considered configuration

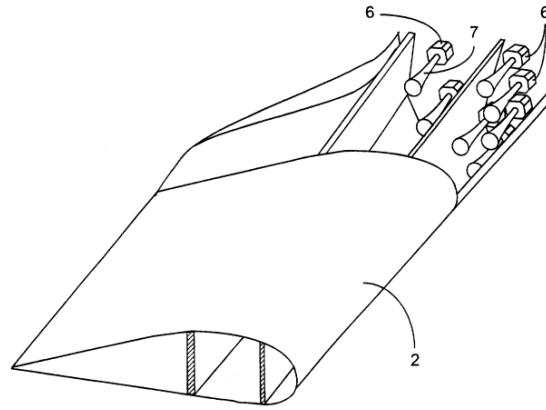


Figure 2.15: Schematic of one of the configurations proposed by LM Glasfiber, where the microwave generators are placed on the blade root (2 - blade; 6 - microwave generators; 7 - horn antennas). Adapted from [63].

is positioning the microwave source in the hub of the bladed rotor, and a hollow conductor with waveguides extends into each blade, targeting front areas prone to icing [64].

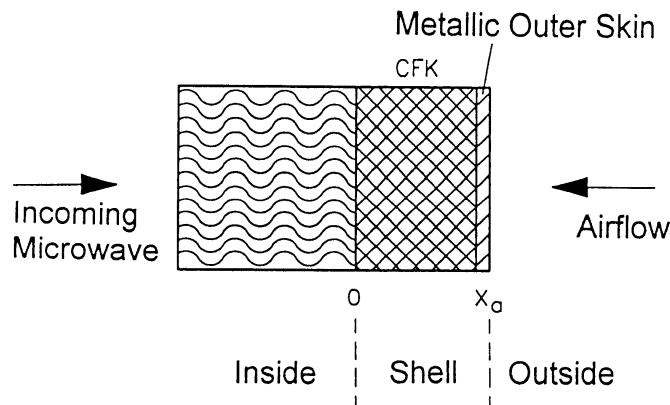


Figure 2.16: Schematic of the structure's configuration proposed by Lambert Feher, in 2002 (CFK corresponds to the carbon fiber). Adapted from [64].

- In 2014, Kenth Johansson *et al.* from various companies and institutes, supported by the Swedish Energy Agency, introduced an innovative approach to anti-icing using a microwave-absorbent coating. This coating, comprising carbon nanotechnology (CNT) particles, absorbs microwave radiation transmitted through a waveguide inside each blade, generating heat, as shown in Figure 2.17. This method can be employed during operation to prevent ice formation and is viable for de-icing strategies. According to the findings from this investigation, this solution uses less energy than other thermal anti-icing and de-icing systems with a relatively low installation cost. The designed coating achieves a favorable balance between microwave reflection and absorption, and it must also be heat-conductive and hydrophobic. However, successful implementation of microwave technology in conjunction with the absorbent coating in wind turbines remains pending [2, 65].

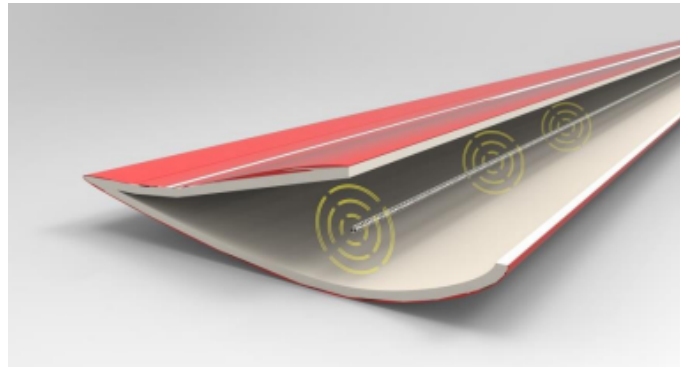


Figure 2.17: Representation of a wind turbine blade anti-icing system using a microwave-absorbent coating [65].

- One of the patents resulted from the project mentioned above was filed in 2015 by Icesolution AS, consisting of a de-icing system using microwave energy absorption. This innovation potentially offers a versatile solution for structures prone to ice accretion, including wind turbine blades, airfoils, aircraft wings, and marine structures. A plurality of solid-state power transistors in combination with an antenna are placed inside a structure such as a wind turbine blade, radiation is generated and absorbed by a coating, focusing on the leading edge of the blade. The solution eliminates the need for expensive high-voltage generators, as solid-state generators require lower voltages, see Section 2.6.1, and increases the system's flexibility [66].

Specifically, the generated microwaves, preferably with frequencies ranging from 900 MHz to 6 GHz, are transmitted through waveguides or antennas to a microwave-absorbing layer, typically comprising carbon nanotubes (CNTs). This layer is attached to the wind turbine blade, covering it entirely or only partially. The power transistors may be coupled via a short waveguide or antennas for direction of the radiation towards the target surface. The selection of transistors, typically ranging from 1 to 20 per m^2 or 0.25 to 5 kW/m^2 , is tailored to meet specific requirements and cost considerations. The practical approach involves heating smaller sections (1-10 m^2) sequentially for efficient de-icing [66].

An alternative configuration proposed by this company contemplates heating the blades when they pass in front of the tower by fixing an emitter on the tower. As the blades rotate, they pass in front of the microwave generators, achieving heating by minimizing the distance between generators and blades. This arrangement could prove beneficial for existing turbines that are challenging to retrofit with internal microwave emitters, although it could introduce other risks and disadvantages, as the microwave source would need to be on the exterior, needing further protection against climatic conditions. It could also be less efficient to heat the blades in an operating wind turbine with this approach, as it would only generate heat inside the absorbing material when the blade passes in front of the emitter [1, 2, 60, 66].

- In 2016, an investigation funded by General Electric, conducted at the Design Laboratory of

the Rensselaer Polytechnic Institute, developed and evaluated a blade de-icing mechanism incorporating a microwave absorbing layer. The design integrates either slotted waveguides or horn antennas for the transmission and emission of microwaves, utilizing magnetrons operating at frequencies of 2.45 or 5.8 GHz. A slotted waveguide is characterized by small apertures along its surface (slots) from which radiation is emitted. The integration of the waveguide within the blade is done by attaching it to the shear web, with the slots facing the leading edge. The microwave absorbing layer is strategically placed near the blade surface, as illustrated in Figure 2.18 [67].

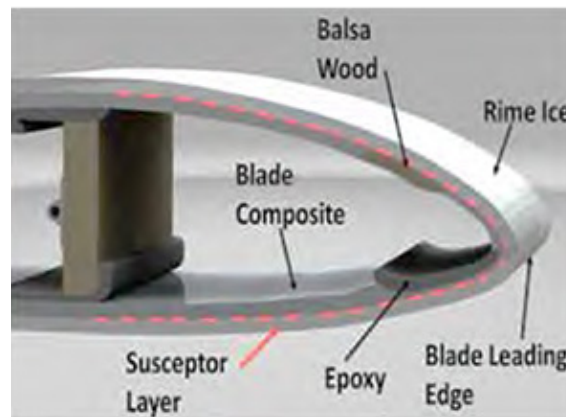


Figure 2.18: Microwave absorbing (susceptor) layer placement on the wind turbine blade [67].

An experimental microwave testing facility was established, wherein a study employing a 1 kW magnetron and a horn antenna was conducted on a small sample of an undisclosed absorbing material with ice, as shown in Figure 2.19. The findings indicated that the ice melted within 30 minutes when subjected to a power density of 1 kW/m^2 [67].

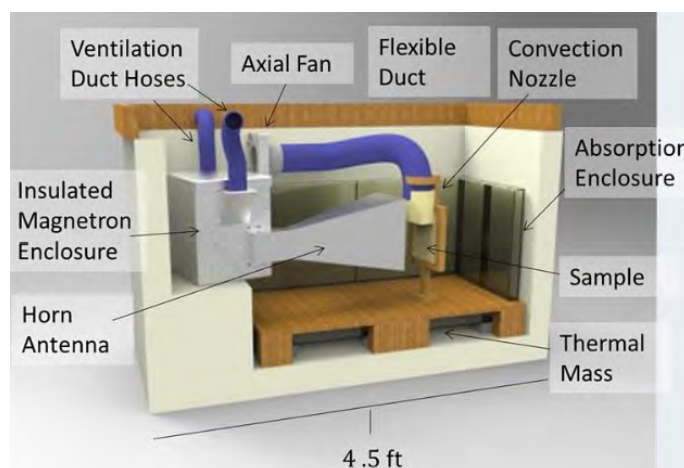


Figure 2.19: Test chamber representation of the Design Laboratory investigation [67].

A subsequent study at the same laboratory, with the same sponsor, aimed to mitigate the effects of multiple reflections within the test chamber by conducting open-air tests. This

study also explored various absorbing materials, including carbon fibers and carbon nanotubes (CNTs) embedded in a polymeric matrix, and conducted a Finite Element Analysis. Although the majority of the results remain undisclosed by the research team, it was observed that CNTs dispersed in polydimethylsiloxane (PDMS) with a thickness of 0.5 mm achieved a heating rate of 46.6 °C/min [67].

- Microwave de-icing technology has also been object of investigation regarding icy roads. Longting Ding *et al.* developed a study in 2018 of a method employing microwave heating for scientific and economical road de-icing in cold regions. In this approach, a magnetron is used to generate microwave energy which is then absorbed by the road material. Since microwave frequency affects the absorption capabilities of a given material, the study compares frequencies of 2.45 GHz and 5.8 GHz [61].

The results revealed that the ice-melting efficiency at 5.8 GHz was 4.31 times higher than that at 2.45 GHz, emphasizing the benefit of higher frequencies. At 5.8 GHz, microwave energy was primarily absorbed by the surface layer of the pavement where was converted into heat, facilitating rapid ice melting. Microwave de-icing demonstrated superior efficiency on cement concrete pavement compared to asphalt concrete [61].

Mingyan Liu *et al.* published an article in 2022, exploring the impact of various microwave-absorbing materials on road de-icing, including magnetite, iron sulfide slag, steel slag, lead–zinc slag, and graphite powder. The study concluded that microwave de-icing efficiency significantly increases with higher content of the absorbing material in cement concrete. In particular, magnetite exhibited good and economical de-icing effects. Additionally, increasing microwave power significantly improved de-icing efficiency [68].

- In 2019, Zehai Zhang *et al.* introduced an original metamaterial absorber (MA) as an alternative to carbon fiber and CNTs coatings for de-icing wind turbine blades using microwave radiation at 2.45 GHz. Through rigorous simulation and adjustment of metallic elements, this metamaterial achieves absorption of almost entirely incident microwaves at a specific frequency, converting it into heat. Multi-physical simulation analysed heat generation, thermal distribution, and temperature rise of the absorber under microwave radiation, with the heating source being either an industrial magnetron or solid-state generators [69].

The original form of the material is a Metamaterial Perfect Absorber, which consists of two distinct metallic elements and a dielectric layer between them. As a result of its straightforward and centrally symmetric feature, the hollow square ring was selected as the metamaterial's front metallic pattern. The middle dielectric layer is made of FR-4 with a thickness of 2 mm, while the back film and the metallic ring are composed of 18 μm copper films. The metallic back film allows for reflection at the back surface of the absorber, which will prevent transmission and increase absorption. Conceptually, the microwave source can be

placed inside the blade, fixed on the web, emitting microwaves through an antenna to penetrate the balsa wood or other supporting materials, reaching the metamaterial that covers the entire outer surface of the blade, as illustrated in Figure 2.20 [69].

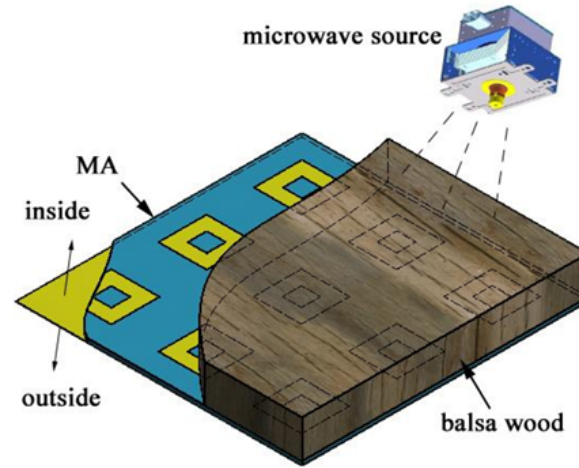


Figure 2.20: Schematic representation of the system proposed by Zehai Zhang et al. in a portion of the wind turbine blade [69].

- In 2021, Ruiliang Luo *et al.* designed a de-icing device for a wind turbine blade based on microwaves and ultrasonic waves. The system employs a magnetron converting electric energy into microwaves that are transmitted directionally through a microwave antenna to elevate the ice surface temperature for de-icing. To optimize conversion efficiency, the research team selected a 2.45 GHz air-cooled magnetron with a maximum output power of 1 kW and a conversion efficiency higher than 70%. After comparative study of various antennas, a horn antenna was considered more appropriate for the system due to its significant power capacity, ease of shaping, and basic structure. It transmits microwave energy on the wind blade substrate to generate heat for de-icing. Simulation results indicated that the antenna effectively concentrated heating in the region facing the microwave antenna outlet, showcasing its efficacy in microwave aggregation and targeted heating [70].

Chapter 3

Initial Modeling and Validation

3.1 Objectives and Motivation

Comparative analysis is a foundational step in scientific and engineering investigations, enabling researchers to leverage existing knowledge and methodologies. This chapter aims to conduct a comprehensive benchmarking review to validate the simulation approach that will be used for the microwave anti-icing system.

For a better comprehension of the fundamental principles addressed in this dissertation, the mathematical formulation behind phenomena such as electromagnetic fields, electromagnetic heating, and microwave absorption are detailed in [Appendix A](#).

Microwave heating, particularly in the food industry, and microwave absorbing materials have been extensively studied. However, the application of microwave heating for anti-icing is relatively underexplored, especially outside traditional cavity configurations, as domestic or industrial microwave ovens, for example. The primary goal of this literature analysis is to provide a robust foundation for the multiphysics simulations to be developed in this work. Currently, there is a notable absence of publicly available software simulations tailored for microwave anti-icing systems or analogous studies involving microwave absorbing layers in free-space environments.

To ensure a rigorous initial analysis and validation using COMSOL Multiphysics software, it is crucial to identify studies that include detailed material properties of the absorbers used. This information is vital for validating the modeling process and ensuring accurate results.

Given the scarcity of directly relevant studies, the literature scope has been extended to include simulations of microwave ovens. This approach is justified by several factors:

- Extensive literature: numerous studies provide numerical modeling in COMSOL along with experimental validation, offering a rich source of validated methodologies.
- Electromagnetic heating similarities: both applications involve electromagnetic heating of microwave-absorbing materials, ensuring conceptual alignment.
- Simplified models and boundary conditions: microwave oven studies often feature simpler models and boundary conditions, facilitating a more straightforward adaptation process.

- Documented material properties: available studies frequently include comprehensive documentation of the properties of absorber materials used, which is essential for accurate simulation and validation.

This chapter begins with a brief introduction to the software used and systematically reviews the relevant literature, focusing on studies that provide detailed material properties and experimentally validated modeling approaches. The process of obtaining microwave oven models will be thoroughly explained, including the specific mathematical formulations and simulation setup details. Finally, the simulation results will be compared to the selected studies to validate the developed models.

3.2 Introduction to COMSOL Multiphysics

In this dissertation, the simulations will be conducted using COMSOL Multiphysics, a comprehensive general-purpose simulation software renowned for its advanced numerical methods. The software's complete modeling workflow, from geometry creation to results evaluation, facilitates the simulation of real-world designs, devices, and processes, offering single-physics and fully coupled multiphysics modeling capabilities [71].

A key feature of COMSOL is its user-friendly interface for building and deploying simulation applications. Within the context of this study, the RF (radio-frequency) Module of COMSOL will be particularly significant. The RF Module is designed to simulate systems where electromagnetic wave propagation in high-frequency applications needs to be analysed [71, 72].

Specifically, the *Microwave Heating* interface in COMSOL will be employed to model electromagnetic heating for systems with frequencies within the microwave's range. This physical model integrates an *Electromagnetic Waves, Frequency Domain* interface and a *Heat Transfer in Solids* interface, allowing for the simulation of cases where the electromagnetic losses behave as the heat source. The coupling of these interfaces assumes that the electromagnetic cycle time is short compared to the thermal time scale, and ensures that electromagnetic material properties can be temperature-dependent, offering a realistic depiction of heating processes [73].

This modeling approach is particularly well-suited for the study of microwave heating for blade de-icing explored in this dissertation. However, despite COMSOL's straightforward workflow, it becomes crucial to understand the mathematical formulation, see Appendix A, behind this physical modeling, to fully comprehend the simulations' setup and to correctly extract valuable data from the results.

3.3 Microwave Ovens 3D Models

After conducting a literature review on investigations regarding microwave heating of an absorber, with multiphysics simulation and validation, three different studies were selected for the initial

stage. These works include: modeling of a microwave oven in COMSOL; properties of the microwave absorbing material, which is Silicon Carbide (SiC) in all cases; analysis of microwave heating of SiC; and experimental work for the validation of results.

In these investigations, the main goal is to examine the behavior of SiC as a susceptor material (materials specifically designed to enhance microwave heating). Susceptors must demonstrate excellent microwave absorption capabilities, and, therefore, these studies focus on assessing SiC's ability to absorb microwaves within a microwave oven. Although this setup does not directly represent a microwave anti-icing system, it allows to establish a starting point for further simulations. While a microwave system inside a wind turbine blade will have major differences in terms of geometry and boundary conditions compared to a microwave oven, the modeling of microwave emission from a source and absorption by a specific material will fundamentally remain the same.

Table 3.1 summarizes the general information about each one of the selected studies. The "Designation" column introduces how each study will be further mentioned along this chapter. Microwave frequency is 2.45 GHz for every study, as this is the most common frequency for commercialized magnetrons. The "HT domain" column details in which domains (listed in Figure 3.1) the heat transfer is being calculated. Some studies only compute the heat transfer in the absorbing material, as the other domains will not have power dissipation (or negligible) and, therefore, will not have heat generation inside. Although a complete analysis can include heat modeling on all domains to simulate heat transfer outside the absorber, in some cases, the correct definition of boundary conditions can help avoid the need to simulate the entire geometry.

Table 3.1: General information about the selected studies

Designation	Walls material	Frequency (GHz)	Power (W)	HT domain	Mesh analysis	Reference
Study 1	Copper	2.45	1200	All domains	Yes	[57]
Study 2	Copper	2.45	900	Absorber	Yes	[74]
Study 3	Copper	2.45	700	Absorber	Yes	[75]

The three different 3D models are shown in Figure 3.1.

It is important to note that, even though these studies provide the absorber's properties and the main simulation setup conditions, they do not serve as tutorials. Consequently, the modeling process remains iterative, and the implications of these iterations will be evaluated when validating the simulations.

The main mathematical formulation detailed in Appendix A is applicable on microwave heating inside cavities, as previously discussed. However, there are still information particular to microwave heating models in COMSOL. When performing numerical simulations, it is essential to define boundary conditions to simulate reality as accurately as possible, and to better understand these conditions, we need to examine their mathematical formulation. Appendix B focus on the boundary conditions and their respective mathematical formulation used in the COMSOL microwave heating models.

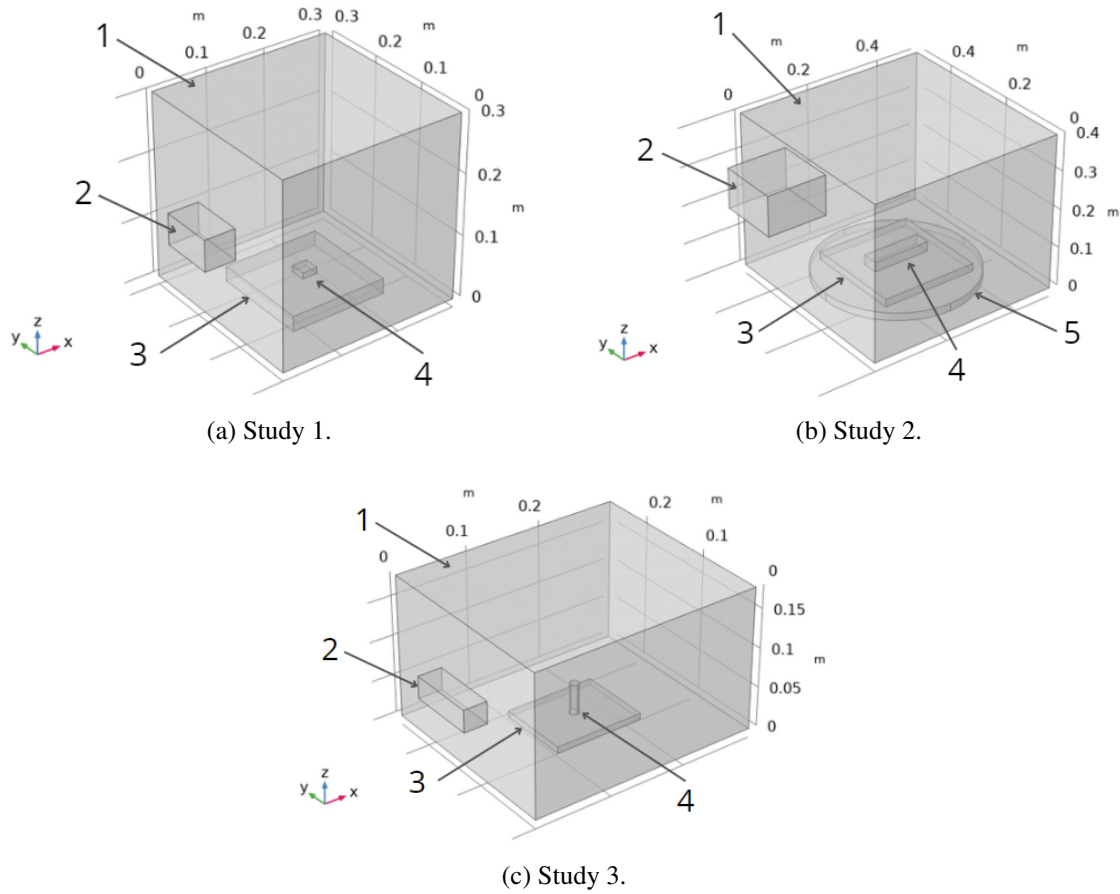


Figure 3.1: 3D Models of the selected studies. 1 - cavity; 2 - waveguide; 3 - base; 4 - absorber; 5 - glass plate.

3.3.1 Simulation Setup and Parameters

In order to obtain accurate and comparable models to those from the three studies, all the available information regarding the simulation setup and its parameters was collected and is shown in Table 3.2. As shown, the dimensions used vary for each study, despite having the same main components: absorber, cavity, and waveguide. The "Thermal BC" column refers to the thermal boundary conditions applied to the exterior boundaries. Study 1 simulated both with and without casket insulation, but for the purpose of this work it was only considered the simulations without casket. The information regarding the different material properties used in each study is presented in Appendix C.

Adding to the thermal boundary conditions, there are also boundary conditions for the electromagnetic field. All three studies use the same boundary conditions for this case: a port boundary condition (PBC) and an impedance boundary condition (IBC), described in Appendix B. The PBC is applied at the rectangular waveguide end and the IBC is adopted for the microwave cavity and waveguide metallic walls.

Table 3.2: Parameters of each study (frequency-transient study is represented by FT)

Designation	Absorber dimensions (mm ³)	Cavity dimensions (mm ³)	Waveguide dimensions (mm ³)	Duration (s)	Thermal BC	Study
Study 1	25 × 25 × 10	300 × 300 × 300	No data	900	No data	FT
Study 2	150 × 40 × 25	500 × 500 × 400	110 × 100 × 100	300	Insulated	FT - 1 way coupled
Study 3	D12 × 38	294 × 254 × 180	30 × 85 × 28	300	Heat flux	FT

Regarding the type of study selected, the distinction between *frequency-transient* and *frequency-transient, one-way coupled electromagnetic heating* is as follows: the former involves a bidirectional coupling between a frequency-domain electromagnetic analysis and a time-dependent thermal analysis, with Maxwell's equations being recalculated whenever the material properties undergo significant changes; the latter sequentially computes the electromagnetic field distribution in the frequency domain, followed by the temporal evolution of temperature changes.

These studies also included some assumptions:

- The absorber is considered isotropic and homogeneous, with initial temperature assumed to be 293.15 K (for the absorber and the remaining domains).
- The dielectric loss factor and mass transfer of air is assumed to be negligible.
- The port is excited by the transverse electric field operating in *z*-direction.

As previously mentioned, these studies are not intended to serve as tutorials for microwave heating modeling. Consequently, there is a lack of detailed information regarding the simulation setup and certain parameters. The missing information is enumerated as follows:

- Study 1: properties of SiC (besides permittivity and permeability); dimensions and properties of base material; waveguide dimensions; convection and radiation modeling; electric displacement field model; solver configurations.
- Study 2: dimensions and properties of glass plate; waveguide exact positioning; electric displacement field model; solver configurations.
- Study 3: electric displacement field model; solver configurations.

To address these challenges, an exhaustive iterative process was undertaken for each study to achieve accurate results. The information regarding process iterations, assumptions, and final considerations made are described in Appendix D.

Analysing the above enumeration, it is evident that Study 1 has a significant amount of missing information, while Study 2 and Study 3 are only lacking a few parameters. As will be detailed

in the next section, similar results will be easier to achieve for models regarding Study 2 and Study 3. One of the main difficulties encountered through the iterative processes described in Appendix D was finding the most suitable method of modeling convection in Study 1, as there are a variety of methods available in COMSOL for simulating this phenomenon, some of which are computationally intensive. The amount of missing properties also increased substantially the difficulty to reproduce the results of this work.

Another crucial parameter in any numerical simulation is the discretization of the modeling space using a mesh. This mesh enables the approximate solution of the problem by solving it at discrete points in space. As the mesh is refined, the solution tends to yield more accurate results. The comparison between the meshes used and the ones from the respective studies are presented in Appendix D.

3.4 Results and Validation

Following the development process outlined in the previous section and detailed in Appendix D, the final results were obtained utilizing the simulation setup and parameters of each respective study. SiC is a non-magnetic material, characterized by a relative permeability of 1. Consequently, power losses in SiC arise solely from dielectric losses, referred to as resistive losses in COMSOL.

3.4.1 Study 1

In this study, the permittivity of SiC varies with temperature, as detailed in Appendix C. Consequently, the electric field and power loss vary throughout the simulation period.

Study 1 also examines the absorption parameters of SiC as they change with temperature, specifically focusing on loss tangent, reflection loss, and penetration depth. These parameters were calculated and compared to those reported in the study, yielding consistent results that validate the accuracy of the calculations. Additionally, the degree of impedance matching (Z) and attenuation (α), see Section A.3.1, were calculated over the same temperature range. These parameters were plotted for temperatures from 0 to 1500 °C, in order to capture all its relevant variations, and are presented in Appendix E.

Power losses (W/m^3) and temperature (°C), obtained for a simulation time of 900 s, are shown in a xz -plane, located at half length of the cavity, in Figure 3.2.

The development from the initial considerations to the final results from the model based on Study 1 is detailed in Appendix D. Due to the necessary assumptions made, the final results presented significant differences.

Table 3.3 compares the values obtained for maximum temperature, maximum electric field magnitude, and maximum power loss density to those reported in the study. The comparison is performed using the maximum values as they are the only published values in the studies. The spatial distributions of these physical variables are presented in Appendix F, where they are compared to the results published in Study 1.

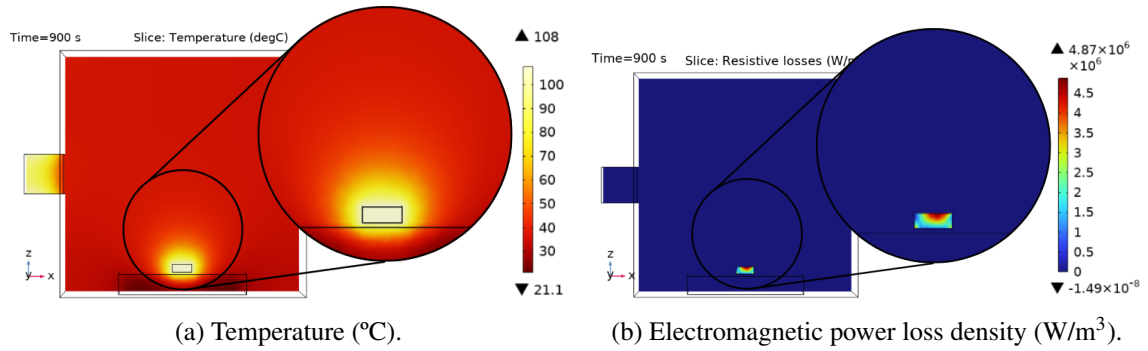


Figure 3.2: Results obtained for model based on Study 1.

Table 3.3: Comparison between results obtained and simulation results from study 1

	Max. temperature (K)	Max. E-field norm (V/m)	Max. power loss density (W/m ³)
Developed model	381.2	6.92E4	4.87E6
Model from study 1	353.2	7.98E4	1.08E6
Models difference (%)	7.9	13.3	350

For validation of these initial models, the success criteria is defined as a maximum relative difference of 15% for each parameter. As presented in Table 3.3 the maximum value obtained for power loss density is 350 % higher than the result from Study 1, or approximately 4.5 times greater. None of the parametric sweeps conducted on material properties yielded similar values for this parameter, consistently resulting in significantly higher values. Variations in thermal properties, convection, and radiation modeling would not influence this variable. This indicates that the relative permittivity used in the simulation of Study 1 differs from the expressions considered in Table C.1. Consequently, this simulation was unable to achieve sufficiently similar results for successful validation.

3.4.2 Study 2

This work employs constant values of permittivity and permeability, indicating that these properties remain unchanged with temperature. Consequently, the electric field and power loss distributions remain constant throughout the simulation period. By utilizing a *frequency-transient, one-way coupled electromagnetic heating* study, with heat transfer only solved for the absorber domain, the computational effort and solving time were significantly reduced.

Study 2 does not include any analysis on absorption parameters of SiC, and for this reason they were not calculated. Power losses (W/m³) and temperature (°C) distributions, obtained for a simulation time of 300 s, are shown in a *xz*-plane, located at half length of the cavity, in Figure 3.3.

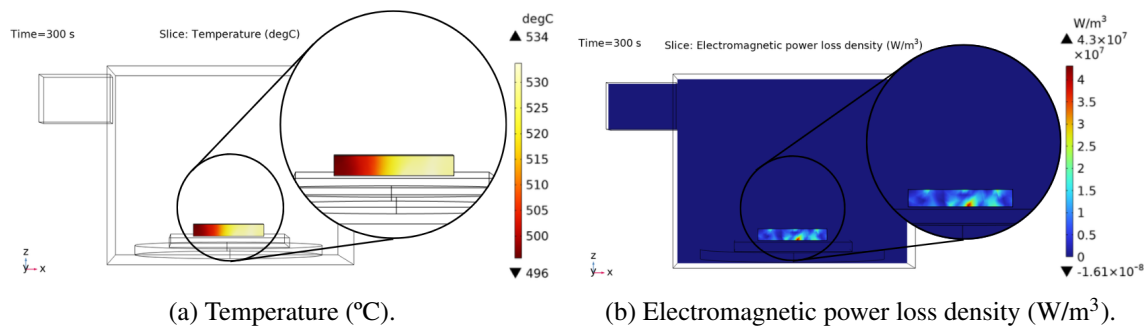


Figure 3.3: Results obtained for model based on Study 2.

As previously mentioned, Study 2 did not provide all the detailed parameters, and the assumptions made are explained in Appendix D. These final considerations may not precisely correspond to the setup used by the study's authors, therefore the results obtained were not exactly identical.

In this case, only temperature and electric field magnitude were evaluated in Study 2 for this geometry. Therefore, only these parameters are compared in Table 3.4 and Appendix F. Table 3.4 shows a comparison between the maximum values of temperature and electric field norm, while Appendix F presents a comparison of the spacial distributions of these two parameters.

Table 3.4: Comparison between results obtained and simulation results from study 2

	Max. temperature (K)	Max. E-field norm (V/m)
Developed model	807.0	6.53E4
Model from study 2	815.2	7.21E4
Models difference (%)	1.0	9.4

Table 3.4 shows that the maximum temperature and electric field norm obtained were only 1.01 % and 9.43 % lower, respectively, than the values reported in the study, demonstrating a high degree of similarity, with a relative difference lower than the defined success criteria of 15%.

Since Study 2 includes experimental validation for the maximum temperature increase, a comparison was made between the results achieved in this work and the results published by Study 2, derived from both numerical simulation and experimental work. These comparative evaluation is shown in Figure 3.4. The similarity between the results obtained in this work and those reported in Study 2 validates this model, given the mentioned assumptions and considerations.

3.4.3 Study 3

In this study, permittivity of SiC also changes with temperature, as shown in Appendix C. Therefore, electric field and power loss distributions will also change throughout the simulation time.

Similarly to Study 2, Study 3 does not include any analysis on absorption parameters of SiC, despite their variation with temperature, and therefore they were not calculated. Power losses

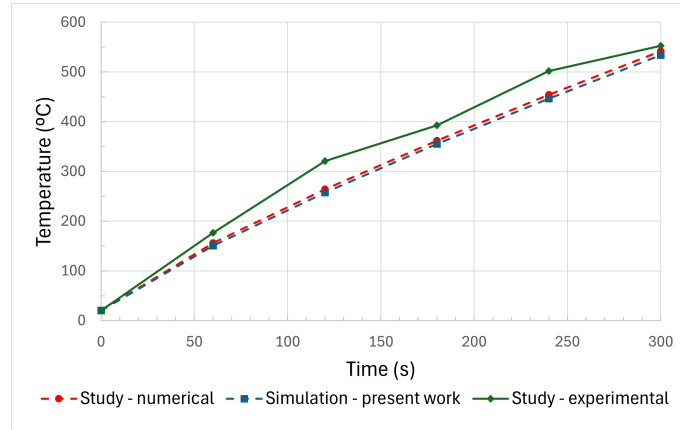


Figure 3.4: Comparison of the maximum temperature variation between simulation of the present work, and simulation/experimental results from study 2.

(W/m^3) and temperature ($^{\circ}\text{C}$) distributions, obtained for a simulation time of 300 s, are shown in a xz -plane, located at half length of the cavity, in Figure 3.5.

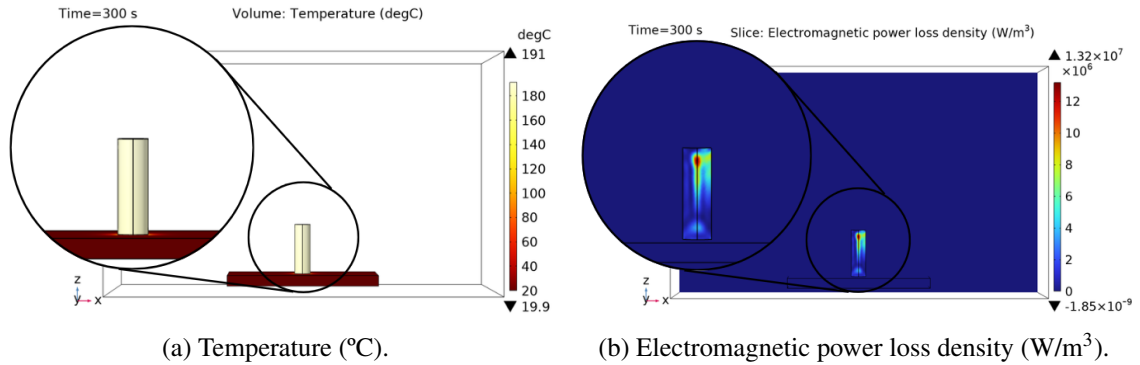


Figure 3.5: Results obtained for model based on Study 3.

Study 3 also did not provide all the detailed parameters for the simulation setup, and the assumptions made are also explained in Appendix D. Therefore, the same reason presented before for Study 2, for not achieving exactly identical results, can be applied here in an analogous way.

In this study, temperature, electric field magnitude, and power loss density were evaluated. Consequently, these parameters are compared in Table 3.5 and Appendix F. Table 3.5 shows a comparison between the maximum values of temperature, electric field norm, and power loss density, while Appendix F presents a comparison of the spacial distributions of these parameters.

Table 3.5 shows that the maximum temperature, electric field norm, and power loss density obtained were 0.02 %, 28.4 %, and 10.9 % higher, respectively, than the values reported in Study 3. The differences are lower than the success criteria of 15%, except for electric field magnitude. However, as it can be seen in Appendix F, a careful consideration of electric-field distribution shows that this discrepancy is only significant near the top surface of the absorber, on a small point near the edge, where the electric field is maximum. Possibly a small difference in mesh refinement

Table 3.5: Comparison between results obtained and simulation results from study 3

	Max. temperature (K)	Max. E-field norm (V/m)	Max. power loss density (W/m ³)
Developed model	464.3	7.84E4	1.32E7
Model from study 3	464.2	5.61E4	1.19E7
Models difference (%)	0.02	28.4	10.9

near the boundary is in the origin of this difference, and consequently it was considered irrelevant.

Study 3 also includes experimental validation for the temperature increase. Therefore, a comparison was made between the results obtained in this work and the results shown in Study 3, from both numerical simulation and experimental work, and is shown in Figure 3.6.

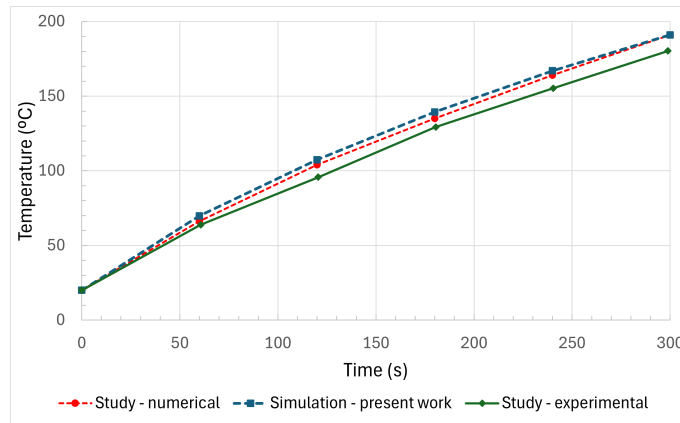


Figure 3.6: Comparison of the maximum temperature variation between simulation of the present work, and simulation/experimental results from study 3.

The similarity between the results obtained in this work and those reported in Study 3, either numerical or experimental, shown in Figure 3.6, indicates that this model can be validated.

In conclusion, only the models based on Study 2 and Study 3 have produced results comparable to their counterparts in the literature, and are suitable for further analysis. As discussed earlier in this chapter, this study and comparison with reference models only validate the initial steps of the modeling approach that will be further developed for the microwave anti-icing system. The intention is to progressively refine and adjust these models to achieve a realistic simulation of this technology inside a wind turbine blade.

Chapter 4

Microwave Anti-icing Solution

This chapter presents the proposed solution for the microwave anti-icing system of a wind turbine blade. As discussed in Chapter 2, the explored and researched solutions for this system are variations on common principles. However, despite the various proposed systems documented in studies, investigations, and even patented innovations, no microwave anti-icing system is currently available on the market. A significant knowledge gap persists regarding the real-world performance of these systems on a full-scale wind turbine.

The existing research indicates that a thorough investigation into the viability of these systems has yet to be conducted. Therefore, this work attempts to evaluate the potential efficiency and competitiveness of microwave anti-icing systems in comparison to existing anti-icing and de-icing technologies. To achieve this, it is crucial to delineate not only the potential designs and operational principles but also the essential system requirements.

4.1 Objectives and Methodology

To study the viability of a microwave anti-icing system, it is crucial to first determine how the system operates and how it can be integrated into a wind turbine blade. The primary objective of this chapter is to address these two questions, thereby facilitating further investigation into the practical application of these concepts.

Initially, the chapter outlines the proposed general solution and working principles of the microwave anti-icing system, followed by the presentation of several potential designs. As with any anti-icing technology, it is also essential to establish the system requirements to understand the necessary criteria for successful implementation.

Subsequently, the chapter emphasizes a critical aspect of any microwave heating system: the microwave absorbing material. Selecting an appropriate material is essential for achieving an efficient system. Therefore, several materials are chosen based on predefined criteria to ensure that the system requirements are met without compromising the overall functionality of the wind turbine.

Finally, the selected materials are tested, using the previously validated microwave oven models, to compare their performance and determine the most suitable options and optimal thicknesses for successful implementation.

4.2 Proposed Solution and Possible Designs

Drawing upon the insights obtained from the comprehensive literature review, this dissertation introduces several potential designs that could be effectively integrated into a wind turbine blade.

4.2.1 Working Principle

The working principle of the established solution can be delineated in 4 main phases, illustrated in Figure 4.1.

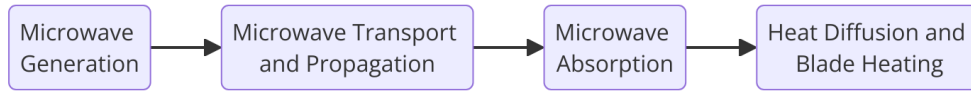


Figure 4.1: Main phases of the microwave anti-icing system.

Microwave generation can be performed with any of the components described in Section 2.6.1. For simplicity, there were only designed systems with magnetrons as a generation source. However, all the proposed systems can use solid-state generators instead of magnetrons, with the needed considerations in terms of component dimensions and integration inside the blade. The same power and frequency is possible to obtain with both technologies.

Transport and propagation of microwaves can be subdivided in two stages: propagation of microwaves to transport them from the source to the emitter; and emission of the microwaves towards the target. Depending on the placement of the microwave generation source, the transport phase can involve significant distances or even be disregarded. If the generators are positioned distant from the emitting point, microwaves will be transported through waveguides. Alternatively, if microwave sources are placed along the blade, attached to the shear web, the need for waveguides is eliminated.

The emission phase can also be accomplished through waveguides, using slotted waveguides or waveguides with openings at the desired emission points. Alternatively, antennas can be used to direct the microwaves towards the target, with horn antennas being specifically suitable for this purpose, enhancing microwave dissipation and heat distribution. In the next section, 3D representation will be further detailed, facilitating the comprehension of these configurations.

One of the most critical parts of an effective microwave heating system is the absorption of incident electromagnetic waves. For this purpose, a microwave absorbing layer (MAL) is incorporated into the blade's layered materials. This layer consists of a highly efficient microwave-absorbing material, facilitating the conversion of electromagnetic energy into heat. Ideally, the MAL is positioned near the surface to ensure rapid heating of the blade's exterior through heat

conduction. To protect the absorbing material and maintain the aerodynamic integrity of the blade, the MAL is not considered to be placed on the exterior surface. This positioning is similar to the positioning of the heating elements in current anti-icing systems which use heating resistance.

As the blade materials are mostly transparent to microwaves, electromagnetic energy will reach the MAL without significant attenuation. Special consideration must be given to the lightning protection layer, typically a metallic mesh embedded in the blade laminate. Since metals reflect most incident microwaves, this layer should be placed after the MAL for two reasons: if the waves first interact with the metallic layer, most of the energy will be reflected and not reach the target (Figure 4.2a); adding to this, placing the metal after the MAL allows the energy transmitted through the absorbing material to be reflected back, enhancing absorption (Figure 4.2b).

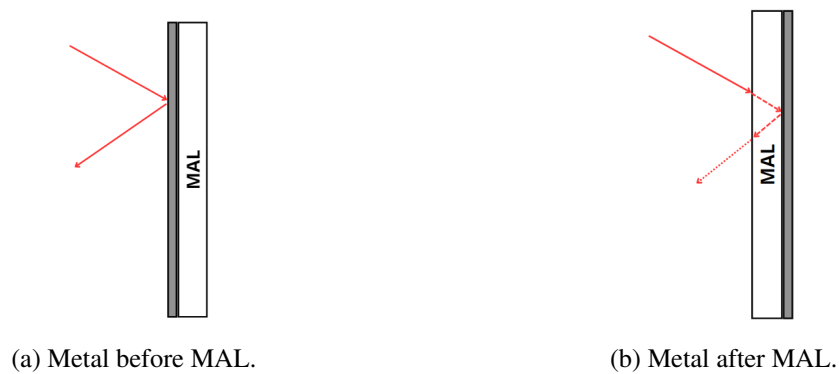


Figure 4.2: Lightning protection layer positioning relative to the MAL.

Finally, after the conversion of electromagnetic energy into heat within the MAL, heat is diffused to the blade surface, raising its temperature above 0 °C to prevent icing. The same principles can be applied to achieve de-icing.

4.2.2 Proposed Designs

The described working principle of a microwave anti-icing system was applied to develop several alternative configurations in COMSOL, utilizing its geometry creation tools. These designs are intended to facilitate the visualization of integrating this technology within a wind turbine blade, rather than detailing the system's construction. The 3D representations focus on a small section of the wind turbine blade, with the understanding that the remaining sections would be similar.

It is important to note that the blade profile changes with distance from the blade root, affecting the available housing space for necessary components. These designs are idealized for a middle blade section; however, as the profile is closer to the tip, accommodating certain components may become challenging. Even if the components fit, this could complicate construction and maintenance. To mitigate this issue, a predefined section near the tip might be designated as component-free, with microwaves directed towards the tip using antennas, such as horn antennas. The detailed exploration of this solution is beyond the scope of this dissertation, and thus, was neither designed nor simulated.

To represent the systems' configurations, the NACA 64-421 airfoil profile was selected, as it represents a cross-section in the mid-span to near-tip region of the blade, and has enough thickness to house the microwave system. Designs incorporating other airfoils are discussed in Appendix G.

As previously mentioned, one alternative involves using slotted waveguides to transport and emit microwaves along the interior of the blade. This configuration requires positioning the microwave sources inside the nacelle or within the blade root. If a single waveguide proves insufficient for emitting microwaves along the entire blade, multiple waveguides can be used. In sections closer to the blade root, it is feasible to accommodate multiple waveguides. Therefore, one waveguide could serve the initial section, another could cover the subsequent section with openings only on that region, and so forth. While optimizing the placement and dimensions of the slots is essential, it lies beyond the scope of this project. Slots can be designed in transverse, longitudinal, or oblique orientations, although only the first two are represented and shown in Figure 4.3.

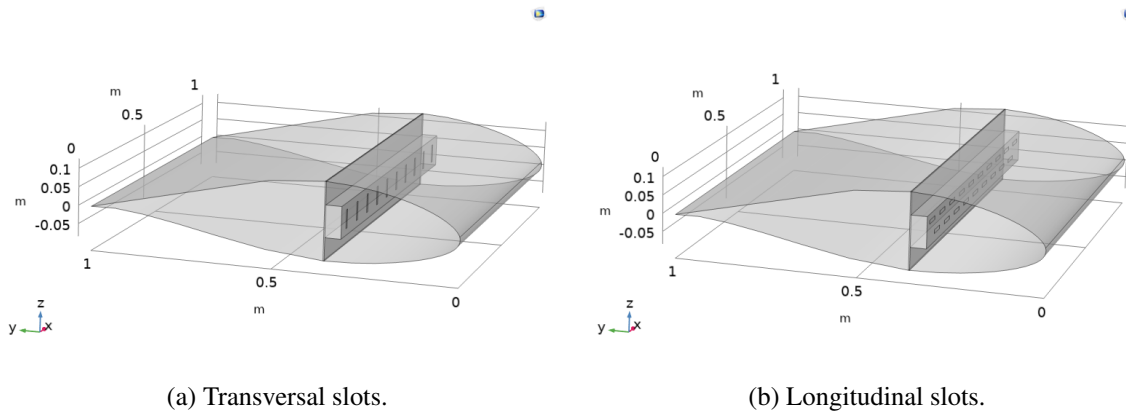


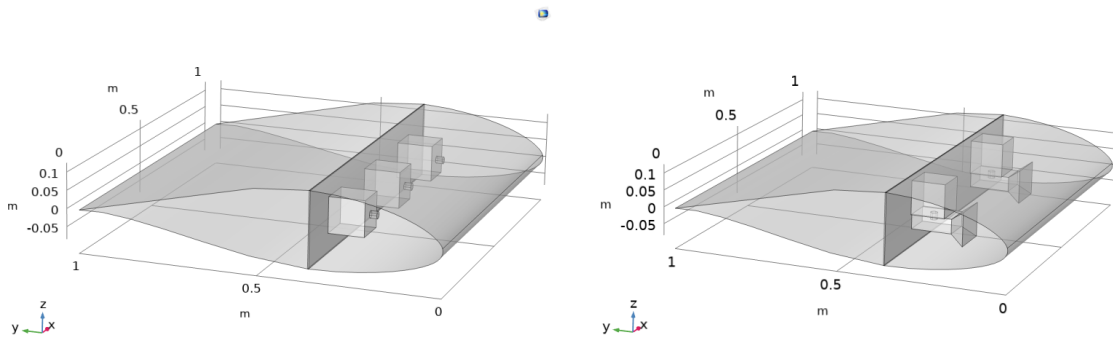
Figure 4.3: Microwave transport and emission through slotted waveguides.

The alternative of placing several sources along the blade is also contemplated, as presented in Figure 4.4. In this representation, the sources are magnetrons attached to the shear web, emitting towards the leading edge of the blade. Two configurations are illustrated: the first shows emission directly through the magnetrons' output antennas (Figure 4.4a), while the second represents magnetrons coupled with small waveguides and horn antennas (Figure 4.4b). The optimal placement and spacing of these sources require further optimization, which will be addressed in Chapter 6.

More configurations could potentially integrate these systems within a blade. Either with different antennas, sources, or positioning strategies for coupling magnetrons with waveguides/horn antennas. However, as the primary objective of this section is to facilitate the visualization of the microwave anti-icing system within a wind turbine blade, it is not intended to exhaustively cover all technological alternatives or detail the specifications of each configuration.

4.3 Anti-icing System Requirements

In order to characterize the microwave anti-icing system, it is essential to define the requirements that the system must fulfill, including the heating power that needs to be supplied to the blade



(a) Magnetron's output antennas emission.

(b) Horn antennas emission.

Figure 4.4: Microwave generation and emission through magnetrons along the blade.

surface (useful heat). Additionally, it is important to establish the constraints of the system, such as maximum temperatures that critical components can reach, maximum available power supply for each blade, material durability, and other factors that will be discussed in this section.

With the system requirements and constraints identified, the optimal trade-off must be determined to ensure that the requirements are met while respecting all constraints.

4.3.1 EES Steady-State Model

To define the system power requirements, a numerical model, for a steady-state regime, was developed using *Engineering Equation Solver* (EES) software. EES is a general numerical equation-solving program chosen for its ease of use and suitability for heat transfer calculations.

The power required by the system for anti-icing can be estimated for any ambient conditions. Simplifying the problem, the required anti-icing power can be defined as the power necessary to maintain the outside surface at a specific temperature, defined as the limit condition below which icing could occur. This calculated power depends solely on the exterior conditions (atmospheric conditions and wind velocity relative to the rotating blade), blade profile and dimensions, and is independent of the heating system. Mathematical formulation of this model and the respective simulation setup is presented in Appendix H.

As the convection coefficient decreases along the airfoil width (distance to the leading edge in the direction of the airfoil chord), see Appendix H, the highest convection coefficient is expected to be near the leading edge, without accounting for airflow acceleration effects in the airfoil surfaces. By approximating the leading edge as a small flat plate with a length of 0.02 m in the direction of the flow, the average convection coefficient can be estimated for this critical region, assuming a laminar boundary layer. Consequently, the power calculated will correspond to the power required to maintain the leading edge surface at a specified temperature. For the remainder of the blade, if the same power is supplied, the surface temperature should exceed the leading edge value.

The results of required power, as a function of relative wind velocity, to keep the blade surface temperature at least at 5 °C, are shown in Figure 4.5, for air temperatures of -10 °C and -20 °C.

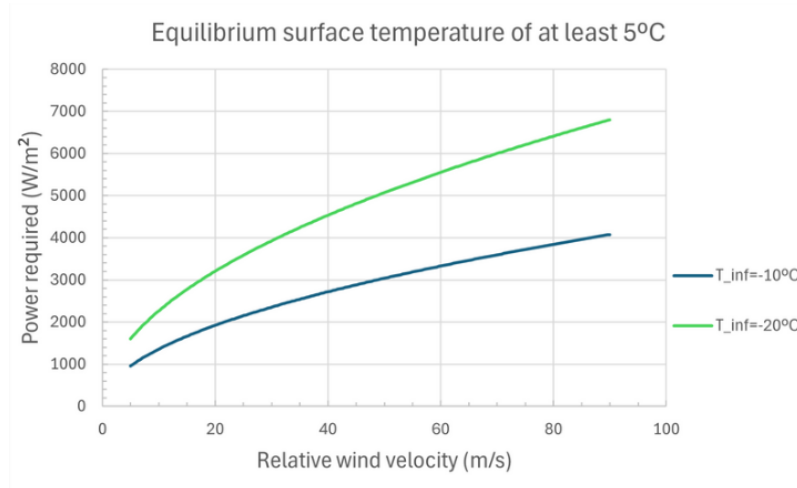


Figure 4.5: Required power to keep the blade surface steady-state temperature at least at 5 °C, as a function of wind relative velocity.

It was also determined with this model that radiation has a minimal impact on power loss from the surface, with convection losses being approximately 100 times greater than radiation losses. Therefore, radiation was not considered in the subsequent analysis.

4.3.2 System Constraints

As previously mentioned, defining system constraints is crucial for developing a reliable and competitive microwave anti-icing technology.

One critical aspect of such a system is the maximum temperature that the blade materials can withstand without compromising their properties. In this thesis, the focus will be the maximum adhesive temperatures, which are particularly used on the shear web and near the leading edge.

For materials with a non-crystalline structure, such as the structural adhesives used in wind turbines, the Glass Transition Temperature (GTT) is a key characteristic. At this temperature, the material transitions from a solid to a rubbery state, losing stiffness, which could impact the structural integrity of the blade [76].

According to DNV-GL, an international certification society, the specifications for wind turbine blades require that the maximum blade temperature is at least 15 °C lower than the GTT of the matrices and adhesives used. In this case, the GTT for the blade adhesive is 70 °C, meaning the maximum allowable blade temperature should be 55 °C [77].

Another important consideration is the power available for each blade. In this study, the maximum power available was taken from [78], based on Vestas anti-icing protection system. For anti-icing mode, there is available from the wind turbine's own energy production between 230 to 280 kW. Considering the maximum value and dividing the total power by the three blades, a power of 93.33 kW per blade is available. If the system is working in de-icing mode, then the power available is 75 kW from the grid for the three blades. De-icing is used for more severe conditions, requiring the turbine to pause operation.

Additionally, the durability of the materials used in the MAL should be discussed. To prevent premature failure and replacement, the MAL's durability should at least match the wind turbine's expected lifetime, which is considered to be 20 years in this investigation.

Furthermore, potential lightning risks introduced by the MAL or the microwave system components (such as sources and waveguides) must be taken into account. The mass added by the microwave system, compared to the current anti-icing system, also requires consideration, as it could lead to increased loads, vibrations, reduced lifespan, and diminished turbine efficiency due to aerodynamic performance degradation.

4.4 MAL Material Selection

As previously mentioned, material selection for the MAL is a key step to achieve an efficient microwave anti-icing system. In order to enhance absorption, it is essential to choose suitable materials for simulation and testing. Accordingly, specific criteria were established to identify a pool of materials that could be integrated into the system.

It is important to emphasize that the objective of this work is not to identify the optimal absorber material for implementation in this anti-icing system. Absorbing materials are a widely studied topic, and a comprehensive definition of the most suitable material for this application would necessitate extensive experimental tests and in-depth research, which are beyond the scope of this project. The intention of this dissertation is to characterize a few potential materials for use in the MAL to assess and analyse the viability of this technology.

4.4.1 Criteria for Material Selection

As discussed in Section 2.6.2, microwave absorbers must exhibit enhanced dielectric and/or magnetic losses, characterized by their relative permittivity (real, ϵ'_r , and imaginary, ϵ''_r) and relative permeability (real, μ'_r , and imaginary, μ''_r) properties. The mentioned section also outlines the types of materials that serve as suitable microwave absorbers: ferrites, magnetic materials, carbon-based materials, and metamaterials.

To identify potential materials, an exhaustive and comprehensive literature review was conducted. Several suitable absorbers identified in the literature (including articles, review papers, supplier data sheets, dissertations, and books) with available electromagnetic properties (permittivity and permeability) were selected. Since these properties vary with frequency, only materials whose frequency range includes 2.45 GHz were chosen, as this is the most common frequency emitted by magnetrons and will therefore be used throughout this dissertation.

To evaluate and compare the different materials, the parameters described in Section A.3.1 can be used. After this initial search, the results were refined and materials were selected based on the following criteria:

- Materials must have values for the real and imaginary parts of both permittivity and permeability at a frequency of 2.45 GHz;

- The absorber should be a composite material, or other type of material which can be integrated within a blade laminate;
- All the other required properties for simulation - density, thermal conductivity and heat capacity - must be available, or at least possible to estimate based on the composite isolated materials;
- Penetration depth (D_p) of the material, see Section A.3.1, should not be very high (attenuation too low) to prevent excessive transmission and degradation of absorption capacities. The lower the penetration depth, the thinner the absorber can be. However, it should still be at least in the order of millimeters, as lower values could result in microwave reflection, as seen in metals. A maximum value of 35 mm for D_p was established;
- A maximum of five different selected materials is set to facilitate simulation and comparison.

4.4.2 Description of Selected Materials and Their Properties

According to the predefined criteria, five materials were selected as suitable microwave absorbers, with the required properties for testing in COMSOL.

The five materials selected with their descriptions are given in Table 4.1.

Table 4.1: Selected materials with descriptions. Weight percentage - wt%; Volume fraction - vf%

Materials	Description
(NBSiC)p	Porous nitride bonded silicon carbide. Ceramic composite material that is formed by bonding SiC grains (80 vf%) using Si_3N_4 as the bonding agent (20 vf%).
MWCNT-PP	Composite with multi-walled carbon nanotubes (3 wt%) dispersed in a polypropylene matrix.
CCFRP	Continuous carbon fiber reinforced polymer (12 vf% of CF). The polymeric matrix is polyamide.
MWCNT-epoxy	Composite with multi-walled carbon nanotubes (10 wt%) dispersed in an epoxy.
Eccosorb BSR-1	Supplied by Laird company, it is a thin, flexible, with high magnetic loss, and electrically non-conductive elastomeric absorber.

The materials properties are shown in Appendix I. Permittivity and permeability are given at frequency of 2.45 GHz, and are constant with temperature. Thermal properties were also considered to be constant with temperature, with values taken from the literature or estimated for a temperature of 20 °C. The references for each material property are also contemplated in Appendix I. The only material given by a microwave absorbing materials supplier is Eccosorb BSR-1. Despite the given properties and characteristics, the full composition of this composite is not disclosed by the company.

4.5 Material Comparison

With the selection of these five materials as suitable absorbers for the microwave anti-icing system, a comparative analysis is necessary to identify the materials most likely to produce optimal results.

However, it is important to note that determining the best material for the MAL would require experimental testing, which is beyond the scope of this dissertation.

To establish a basis for comparing these materials, the models validated in the previous chapter were utilized. Despite these simulations providing valuable insights, the absorption capabilities of each material are also influenced by the dimensions of the absorber. Consequently, the results obtained in each specific study cannot be broadly generalized. To address this limitation, the impact of thickness on each material was further evaluated by calculating relevant absorption parameters, in addition to the simulations conducted on the validated models.

This approach ensures a more comprehensive understanding of how each material may perform under varying conditions, thereby providing a more informed basis for material selection in subsequent simulations.

4.5.1 Simulations on Validated Models

The models based on Study 2 and Study 3 were validated in the previous chapter. By substituting the original absorber material (SiC) with each of the selected alternatives, it is possible to evaluate the absorption capabilities under the conditions specified in each model. Given the significant differences in the setup of the two models, direct comparison between them for each material is challenging. Therefore, the focus will be on comparing the performance of different materials within each model separately.

Firstly, it is necessary to establish the parameters that should be analysed for comparing different absorbers. The most critical parameter for assessing the performance of the MAL in converting microwave energy into heat is the power absorbed by the material, or its absorption efficiency (ratio of power absorbed to the microwave power emitted). Figures 4.6 and 4.7 show power loss and absorption efficiency obtained after simulation on COMSOL models based on Studies 2 and 3, for 300 seconds of simulation time. Eccosorb BSR-1 shows the highest absorption efficiency for both models, followed by CCFRP and MWCNT-PP, by this order.

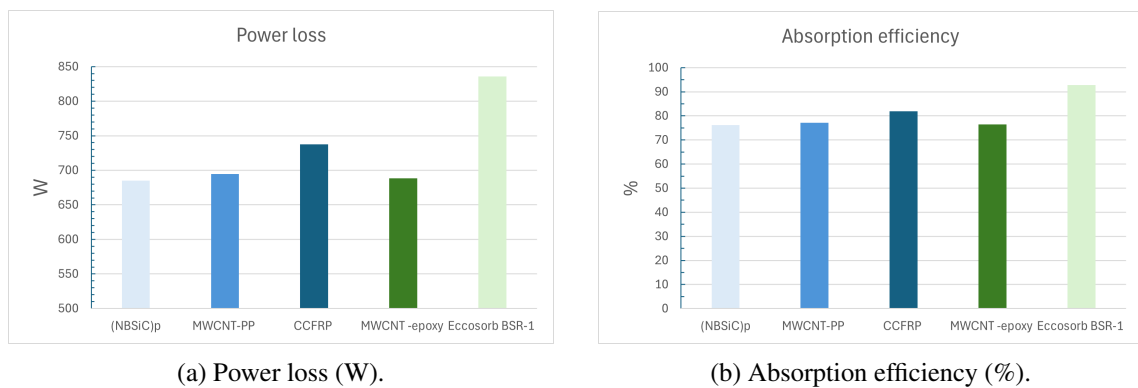


Figure 4.6: Power loss and absorption efficiency for the selected materials, for Model based on Study 2.

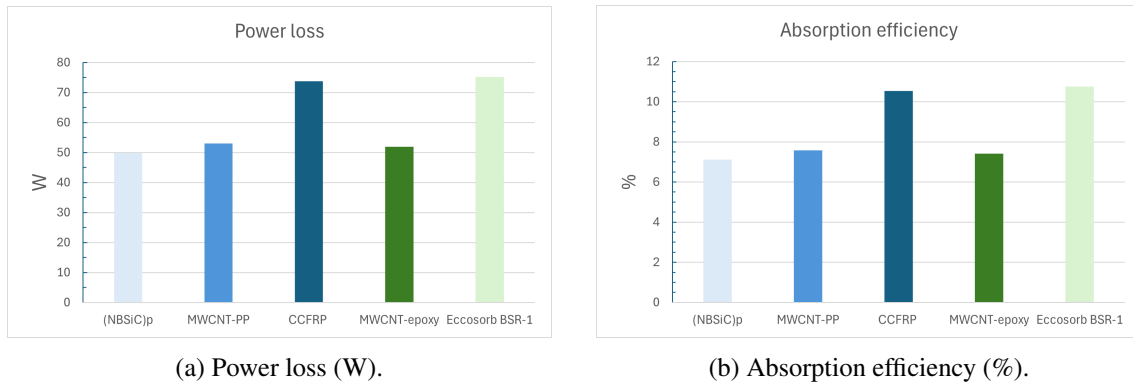


Figure 4.7: Power loss and absorption efficiency for the selected materials, for Model based on Study 3.

It is important to note that these models are either thermally insulated (Study 2) or have negligible losses (Study 3) and assume constant heat generation within the material. Consequently, temperatures will not stabilize at steady-state but will continue to rise until the end of the simulation. Additionally, the absorbers' volume is considerably low, compared to the wind turbine blade structure that will be studied. As a result, the maximum temperatures reached are significantly higher than the temperatures expected in the blade. Materials with low density, high thermal conductivity, or low heat capacity may reach higher temperatures even if they absorb less power.

The temperature increase through the entire simulation time also allows smaller volumes to achieve higher temperatures, despite lower overall power loss, due to faster heating. Therefore, comparing temperature results between the two models, with differing absorber volumes, is not relevant to evaluate the absorption performance. Study 3 models an absorber with a significantly lower volume, which results in lower power absorption and higher temperatures.

Nevertheless, it remains valuable to assess the temperature variation within each individual model, as this provides insights into the materials with faster heating rates, which are influenced by absorbed power, density, and thermal properties, given a constant volume. Figure 4.8 shows the maximum temperatures achieved by each material in both models. Despite the higher power absorbed, Eccosorb BSR-1 demonstrates lower temperature increase due to its high density.

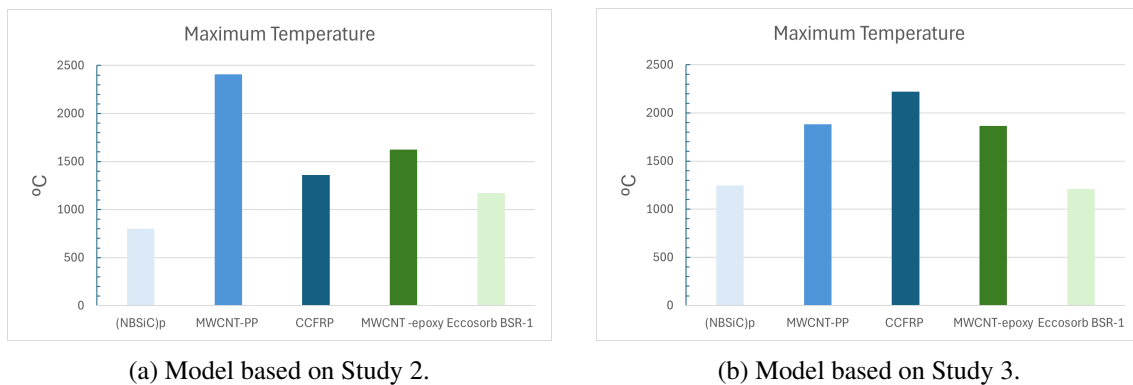


Figure 4.8: Maximum temperatures reached by each selected material, in both models.

Another important parameter for evaluating absorber performance is the temperature homogeneity within the material, which is primarily influenced by thermal conductivity and the spatial distribution of power loss within the absorber.

The distribution of power loss is affected by the spatial variation of the electric field, which depends on numerous factors, including the emission method, placement of the microwave source, system geometry, properties and dimensions of the absorber, frequency, and boundary conditions. Since these models feature metallic walls that reflect microwaves back into the cavity, significant interference between the reflected microwaves occurs, leading to considerable spatial variations in the electric field pattern, and high temperature differences. Figure 4.9 presents the maximum temperature difference within each material for both models. (NBSiC)p has a considerably higher thermal conductivity (k) which allows to achieve an almost homogeneous temperature distribution. On the other hand, MWCNT-PP has significantly higher temperature differences due to very low k .

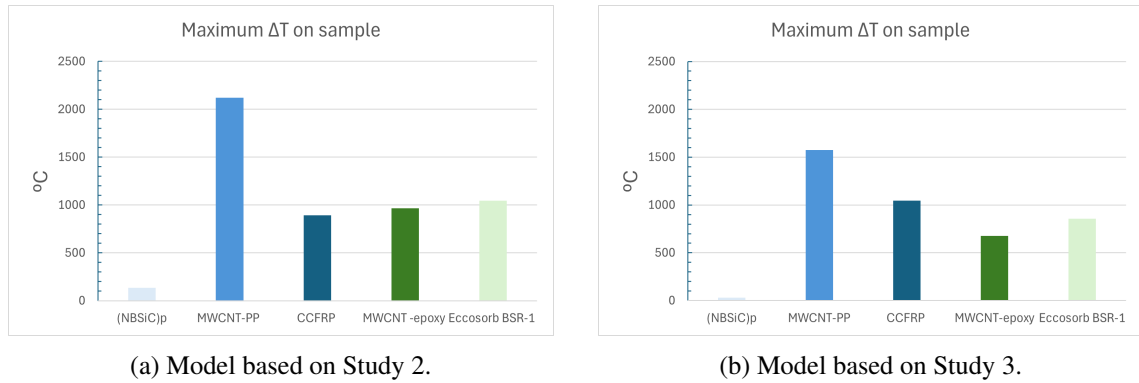


Figure 4.9: Maximum temperature difference within each selected material, in both models.

In addition to the results obtained from the validated COMSOL models, the selected materials can be further compared using the absorption parameters outlined in Section A.3.1. Calculating these parameters can enhance the understanding of the simulation results. The effects of reflection loss (RL) and impedance matching (Z) on absorption efficiency cannot be directly evaluated in these simulations, as the relevant equations are applicable only to perpendicularly incident radiation, whereas in a metallic cavity, microwaves interact with the absorber from multiple directions.

However, attenuation (α) and penetration depth (D_p) remain useful in explaining the results. One of the most significant factors influencing power absorption is the material's ability to absorb the incident microwaves which enter the material. The attenuation and penetration depth for the five materials, at 2.45 GHz, are presented in Figure 4.10. Higher α (corresponding to a lower D_p) generally results in greater microwave absorption and reduced transmission. It is important to note that reflection of incident radiation is not accounted for in these parameters, which also influences absorption efficiency.

Figure 4.10 shows that Eccosorb BSR-1 has significantly higher attenuation, which allows to absorb more energy with reduced thickness. It is also visible that the materials with higher attenuation demonstrated higher absorption efficiencies (Figures 4.6 and 4.7).

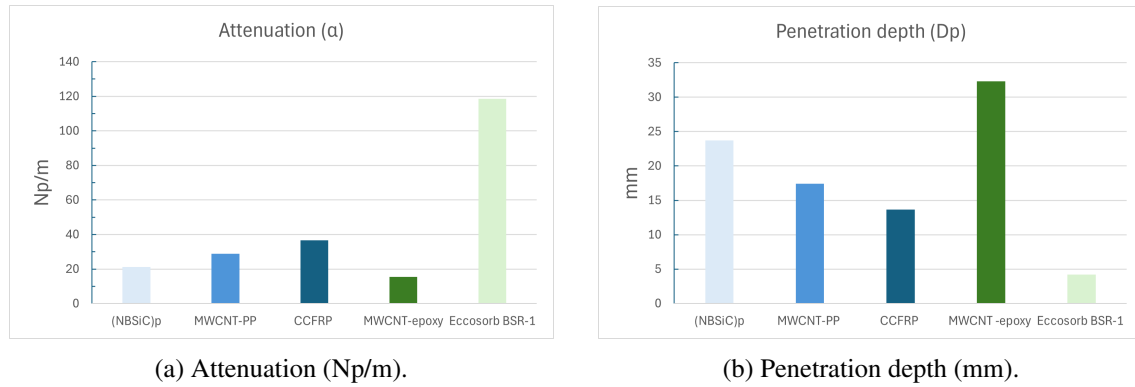


Figure 4.10: Attenuation and penetration depth of the five selected materials, at 2.45 GHz.

4.5.2 Influence of Thickness for Each Material

As discussed in Section A.3.1, thickness influences reflection loss (RL) and the degree of impedance matching (Z). Therefore, analysing how these parameters change with thickness, for each material, is important to characterize the suitability of these materials for the microwave anti-icing system.

Considering perpendicular incident radiation on the MAL, at a frequency of 2.45 GHz, it is possible to determine the optimal thickness for each material that minimizes reflection. The variations in RL and Z with thickness for the five selected materials are detailed in Appendix J.

Table 4.2 presents the optimal thicknesses for each material along with their corresponding RL and Z values. The optimal thickness was identified as the thickness at which RL is minimized within a range of 0 to 20 mm.

Table 4.2: Optimal thickness for selected materials with respective RL and Z

Materials	Optimal Thickness (mm)	RL (dB)	Z
(NBSiC)p	10	-13.2	1.55
MWCNT-PP	10	-18.9	1.04
CCFRP	11	-19.4	0.89
MWCNT-epoxy	10	-6.29	2.12
Eccosorb BSR-1	3.5	-19.6	1.17

Within the considered range of thicknesses, Eccosorb BSR-1, CCFRP, and MWCNT-PP demonstrated superior RL and Z values, as well as higher absorption efficiencies in the COMSOL simulations conducted using the validated models. As a result, these three materials were selected for further analysis and simulations, presented in the next chapter. The variations in D_p and optimal thickness among these materials provide an opportunity to explore different thicknesses for the MAL based on the material selected. Additionally, the distinct thermal properties and densities of these materials will allow for the evaluation of different heating rates and the impact of these properties on the performance of the microwave anti-icing system.

Chapter 5

Simplified Microwave Anti-icing System Models

This chapter introduces the modeling and simulation of the proposed microwave anti-icing system, an essential step following the establishment and description of the solution. Through the use of simplified geometries and assumptions, the foundational analysis for assessing the feasibility of this technology is presented. Furthermore, the outcomes of the modeling and simulation will serve as a preliminary study to support future simulations and experimental investigations, thereby laying the groundwork for future advancements in this innovative anti-icing approach.

The microwave anti-icing system was initially simplified by a flat plate geometry. The initial models presented in Chapter 3 were modified until obtaining a model of the microwave absorbing layer (MAL Model). Following this model, the blade materials were integrated into the flat plate geometry in the Blade Materials Integration Model (BMI Model). Finally, two 2D models of a wind turbine blade cross-section were developed: one with convection losses estimated through a constant convection coefficient; and the other with Computational Fluid Dynamics (CFD) integration to accurately model the airflow around the blade.

5.1 Simplified Blade Geometry

To facilitate the initial analysis, a simplified approach was adopted by representing the wind turbine blade with a flat plate geometry. This choice was made due to the ease of modeling in COMSOL, allowing the focus to remain on the critical aspects of microwave emission and absorption. Despite the geometric differences between a flat plate and a real wind turbine blade, this method still yields valuable insights.

The flat plate model enables the examination of how different materials perform under conditions that closely resemble those within an actual blade, including the integration of blade materials and the simulation of energy losses to both the exterior and interior air. Additionally, this simplified geometry allows for the exploration of various factors, such as the influence of absorber

thickness, variations in microwave power, and changes in external atmospheric conditions, thereby providing a comprehensive analysis for further investigation.

5.1.1 Adaptation of Initial Models

To develop a reliable model for a flat plate, the initially validated models presented in Chapter 3 were used as the foundation. To minimize the risk of inaccuracies in the modeling process, modifications were introduced incrementally. This methodical approach allowed for the individual assessment of each change, ensuring that the effects of each alteration were carefully analysed and understood before proceeding further.

The objective is to develop a model that effectively eliminates the influence of a cavity, typically present in a microwave oven, and ensures that microwaves are emitted perpendicularly to the absorber flat plate without interference from surrounding elements. This approach aims to closely simulate the intended application, where the microwave emitter is attached to the shear web and directs energy towards the blade's inner surface. Since the blade surface is being approximated by a flat plate, the model seeks to exclude the effects of other walls, focusing solely on the interaction between the microwave source and the MAL.

Starting from the initial models (Study 2 and Study 3), five sequentially developed models were implemented in COMSOL, each incorporating gradual modifications:

- **First Flat Plate Models:** The initial models based on Study 2 and Study 3 were modified by altering the absorber geometry to a flat plate with dimensions of 0.2×0.2 m. The absorber thickness for each material was set to the optimal thickness presented in Section 4.5.2, in Table 4.2;
- **Second Flat Plate Models:** to approximate the results between the two models, the microwave power was standardized at 700 W for both, and the cavity dimensions were adjusted to $0.25 \times 0.25 \times 0.25$ m. The waveguide dimensions were also modified to function properly at a frequency of 2.45 GHz. Specifically, a WR-340 waveguide with dimensions of 86.36×43.18 mm was selected;
- **Third Flat Plate Models:** In this iteration, the waveguide was positioned on the top surface of the model, and the same mesh was applied in both models;
- **Fourth Flat Plate Model:** From this point onward, only a single model was developed. The flat plate was integrated into the bottom surface of the cavity (0.25×0.25 m), excluding the base material, and the study was configured as a *frequency-transient* analysis. The bottom surface boundary condition was modified from Impedance to Scattering, which makes a boundary transparent to scattered waves. It still partially reflects a plane wave at oblique incidence.
- **Fifth Flat Plate Model:** The Scattering Boundary Condition was applied to all boundaries, modeling a simplified open boundary without requiring significant computational resources.

The different geometries of each model are presented in Appendix K, and the mesh refinement analysis for these models are presented in Appendix L (Section L.1).

To evaluate the impact of each modification, the absorbed power was obtained in simulations across these five models. This parameter is particularly crucial as it provides insights into how changes in the simulation setup affect the microwave absorption by the MAL. Figure 5.1 shows the variation of this parameter with the sequential changes to the Flat Plate Model. The results are shown for the models where the starting point is the model based on Study 2, since the only major differences to Study 3 are on the First Flat Plate Model, and were considered irrelevant.

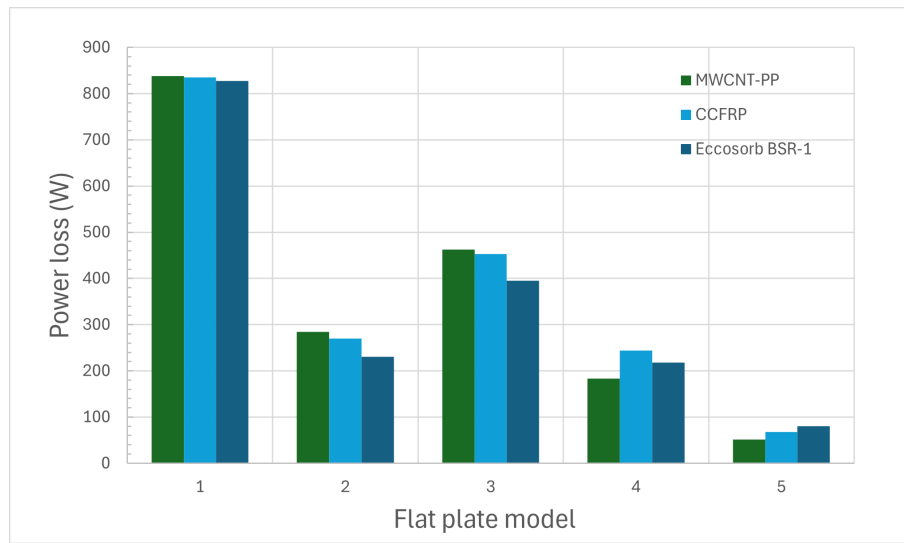


Figure 5.1: Electromagnetic power loss for each Flat Plate Model, for each absorber material.

As shown in Figure 5.1, there is a notable decrease in absorbed power when transitioning from the First to the Second Flat Plate Model, due to the reduction in microwave power and cavity dimensions. However, moving to the Third Flat Plate Model, power absorbed increases, which highlights the influence of the microwave source placement. With the source now positioned on the top surface, the incidence of radiation on the flat plate is enhanced, thereby improving absorption.

The introduction of transmission from the bottom surface in the Fourth Flat Plate Model leads to a decrease in power absorption, as microwaves that previously reflected back to the absorber upon reaching the boundary are now transmitted. Finally, the Fifth Model further reduces absorption by applying the Scattering Boundary Condition (SBC) to all boundaries, which minimizes reflections from the walls back to the absorber. Understanding these effects is essential to ensure that the results align with theoretical expectations.

5.1.2 Microwave Absorbing Layer Model

Following the adaptation of the initial models presented in Chapter 3, through the five models described in the previous section, a final flat plate model for the MAL was successfully developed in which microwaves are emitted and interact with the MAL. In this model, microwaves are

either absorbed by the MAL or lost to the infinite through reflection or transmission. This setup enables the study of the influence of the absorber material and its dimensions without depending on external conditions.

Simulation Setup

This model is a modification of the Fifth Flat Plate Model, maintaining the use of the same physics interfaces, and multiphysics coupling (*Electromagnetic Heating*).

To model more accurate open boundaries around the domain, the Perfectly Matched Layer (PML) feature was used instead of the Scattering Boundary Condition (SBC) used in the Fifth Flat Plate Model. With significantly higher computational effort and solving time, the infinite domain is simulated more accurately, with the incoming waves being absorbed totally, without reflection to the interior.

The electric displacement field in the model is defined using the *Loss Tangent, Dissipation Factor* model for the absorber and the *Relative Permittivity* model for the other domains (see Appendix D). This setup simulates electromagnetic losses by utilizing the real and imaginary parts of relative permittivity and permeability in the MAL. Since resistive losses due to conduction are accounted for in the imaginary part of relative permittivity, it is not necessary to define electrical conductivity for the absorber material. For the other domains, where relative permittivity and permeability are negligible, the chosen electric displacement field model allows for the definition of each material's electrical conductivity.

The microwaves are emitted through a WR-340 waveguide opening (rectangular port), specifically designed to operate at a frequency of 2.45 GHz, and are directed perpendicularly towards the MAL. This COMSOL model is referred to as the Microwave Absorbing Layer Model, or MAL Model, and is shown in Figure 5.2.

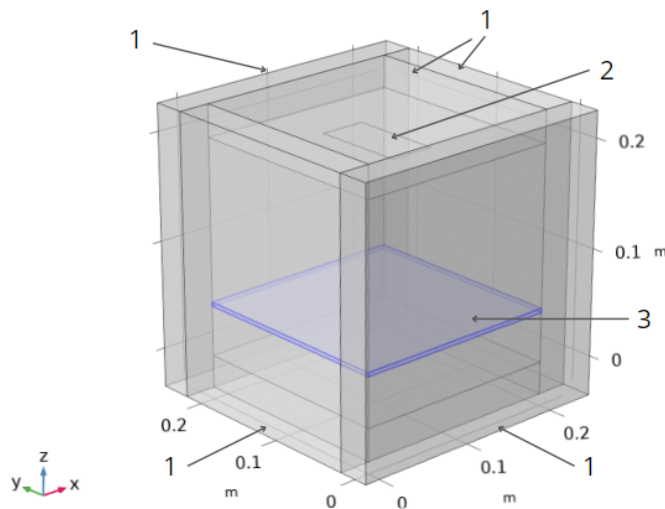


Figure 5.2: MAL Model. 1 - PML; 2 - waveguide opening; 3 - MAL.

PMLs are implemented as domains, rather than boundaries, surrounding the entire simulation domain, as depicted in Figure 5.2. The MAL material was varied among the three selected options, each assigned the respective thickness value provided in Table 4.5.2. The flat plate surface area was defined with dimensions 0.2×0.2 m. All other domains within the simulation, including the PMLs, were defined as air.

The remaining conditions were kept the same from the previous model, including thermal insulation applied to the boundaries of the MAL, and an input power of 700 W. The simulation time is 300 seconds as it allows to observe the model behaviour through a considerable time range without increasing substantially the computational effort. It was implemented a frequency-transient study, similarly to the previous models. The mesh refinement analysis for this model is presented in Appendix L (Section L.2).

Results

The results obtained from the COMSOL simulation of the MAL Model for each absorber material are summarized in Table 5.1.

Although the maximum temperature values do not directly reflect the absorption capacities of each material due to the absence of heat losses, they do offer valuable insights into the heating rates associated with different materials and thicknesses.

Absorption efficiency was calculated as the ratio of absorbed power to the input power. Additionally, the table presents the reflected and transmitted power for each material. It is important to note that the reflected power also includes losses incurred during the propagation of microwaves between the emission source and the top surface of the absorber. These losses, referred to as Travelling Losses, are inherently included in the reflection losses due to the limitations in COMSOL's results analysis, which do not allow the separation of these two components. The power absorbed per area of the MAL surface is also presented in the table.

Table 5.1: Results obtained in the simulations of different absorbers in the MAL Model

Materials	MWCNT-PP	CCFRP	Eccosorb BSR-1
Maximum Temperature (°C)	125	110	228
Power Reflected + Traveling Loss (W)	460	436	364
Power Transmitted (W)	115	103	139
Power Absorbed (W)	125	160	197
Power Absorbed (W/m ²)	3129	4012	4932
Absorption Efficiency (%)	17.9	22.9	28.2

As shown in Table 5.1, Eccosorb BSR-1 demonstrated superior efficiency compared to the other materials, primarily due to its reduced reflection losses. Additionally, it exhibited the highest heating rate, indicated by the maximum temperature achieved at the end of the simulation, which can be attributed to its lower thickness and higher absorbed power.

The efficiency values observed are relatively low, which can be explained by the absence of reflections from the boundaries back to the absorber and the substantial power losses occurring during the propagation between the source and the MAL. In the context of a wind turbine blade, where the MAL is curved rather than a flat plate, the impact of losses through the side walls, which are significant in this model, would likely be diminished.

In this model, the absorption of microwaves for a given material, at a specific frequency and power, depends solely on its ability to minimize reflection and transmission, as there is no reflection from the boundaries. As discussed in Chapter 2 and Appendix A, the absorber's thickness influences both reflection and transmission. Transmission is related to the penetration depth (D_p , equation A.50), which remains constant regardless of thickness. When the absorber thickness is less than D_p , significant transmission occurs, while a thickness greater than D_p results in reduced transmission, with most incident microwaves absorbed before they exit the material.

Reflection, however, is influenced by the reflection loss (RL) and the degree of impedance matching (Z), both of which vary with thickness. Equations A.56 and A.58 only apply to perpendicular incident radiation, which is not the case, as shown in Figure 5.3, which demonstrates the power flow in the MAL Model.

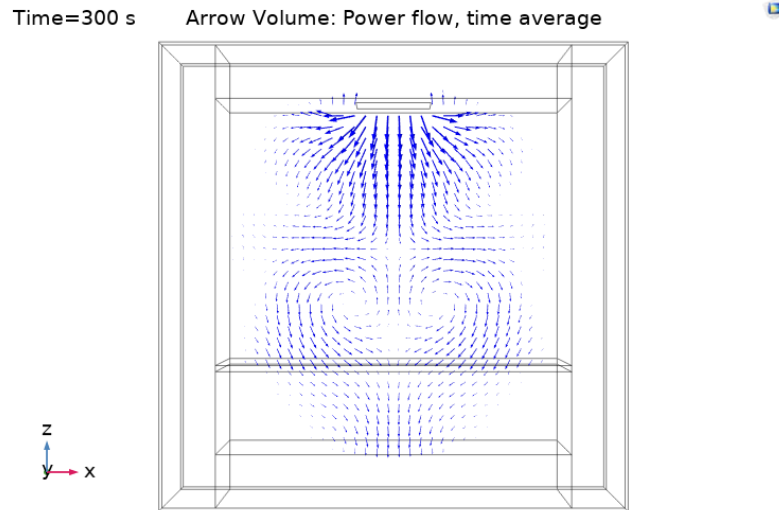


Figure 5.3: MAL Model power flow, for Eccosorb BSR-1. The arrow length is in logarithmic scale to facilitate visualization. The model is represented in the xz -plane.

Figure 5.3, which illustrates the power flow for Eccosorb BSR-1 (representative of the other materials as the flow direction is similar), shows that the direction of power changes during propagation from the source to the MAL. This change is caused by the interference between incident

microwaves and those reflected by the absorber, which alters the electric and magnetic fields' direction.

Given the limitations of relying on RL to obtain the optimal thickness, the thickness of each material was varied in COMSOL to analyse its impact on power absorption. The simulations indicated that the optimal thicknesses for maximizing the power entering the top surface of the absorber (reducing reflection), in this specific model setup, were 20 mm for MWCNT-PP and CCFRP, and 6.5 mm for Eccosorb BSR-1.

5.1.3 Blade Materials Integration Model

To achieve more realistic results for the microwave anti-icing system, it is crucial to incorporate the blade materials into the previously developed model. This integration allows for an examination of the MAL's behavior within the blade laminate and provides insights into how its performance is affected when embedded in the actual blade structure. The simulations performed with this 3D model are also non-stationary.

Simulation Setup

To integrate the blade materials into the simulation, several key considerations were established:

- The analysis utilizes a laminate composition similar to the laminate of a wind turbine within the Vestas portfolio [76];
- The different layers of the wind turbine blade are detailed in Table 5.2 and illustrated in Figure 5.4;
- Given the reduced thickness of each layer, the *Layered Material* feature in COMSOL was employed to model these structures accurately without excessive computational effort;
- Paint, gelcoat, and SPL (lightning protection layer) have constant thickness throughout the blade [77];
- The thickness of GFRP layers varies depending on the radial distance from the hub, but was considered constant in this analysis [77];
- There are also CFRP layers present, although these were not considered for this analysis;
- Adhesive materials, particularly used on the shear web and near the leading edge, were also not considered in this analysis [77];
- While core material is only present in specific parts of the blade cross-section, for this analysis, a constant core thickness was assumed throughout the entire airfoil [76];
- MAL was initially positioned as shown in Table 5.2 and in Figure 5.4;
- Permittivity and permeability were considered to be 1 for all layers (except MAL);

- Internal and external convection losses were simulated with a heat flux boundary condition on the interior and exterior boundaries of the flat plate, respectively;
- Internal heat convection effects were modeled with a constant coefficient of $1.7 \text{ W}/(\text{m}^2 \cdot \text{K})$, in accordance with [77];
- The MAL thickness was defined for each material according to Table 4.5.2, similarly to the previous model.

Table 5.2 presents the properties and thicknesses of each layer, ordering them from the exterior surface to the inner surface of the blade (1-9). Figure 5.4 shows the blade's layered structure, indicating the order in which these layers are placed. For this analysis, the MAL was positioned at layer 5, although further investigation into the placement of the MAL will be carried out in subsequent studies.

Table 5.2: Properties and thicknesses of the different layers. Values with "est." were estimated

Layer	Density (kg/m^3)	Heat Capacity ($\text{J}/(\text{kg} \cdot \text{K})$)	Thermal Conductivity ($\text{W}/(\text{m} \cdot \text{K})$)[76]	Thickness (mm) [76]
1 - Paint	1200 [79]	1000 (est.)	0.2	0.3
2 - Gelcoat	1230 [80]	1000 (est.)	0.682	0.5
3 - SPL	2700 [81]	900 [81]	222	0.35
4 - GFRP	1850 [82]	962 [83]	0.295	1.54
5 - MAL	-	-	-	-
6 - GFRP	1850 [82]	962 [83]	0.295	1.54
7 - Core	559 [84]	1570 [84]	0.037	10
8 - GFRP	1850 [82]	962 [83]	0.295	1.4
9 - GFRP	1850 [82]	962 [83]	0.295	1.4

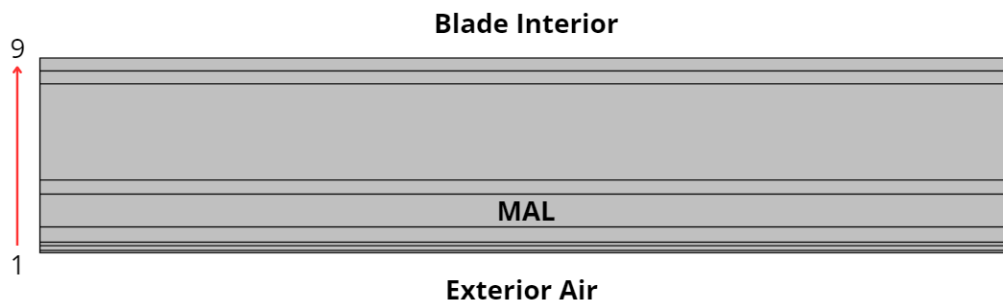


Figure 5.4: Layers considered for the integration of wind turbine blade materials.

Results

Blade Materials Integration Model, or BMI Model, was simulated for the three different absorber materials and the results obtained with a frequency-transient study are shown in Table 5.3. The

maximum and average temperatures of the MAL and the blade's exterior surface, after 300 seconds of simulation, are provided, as well as the power absorbed and the absorption efficiency.

A power of 400 W was applied in this analysis, using the same dimensions as in the MAL Model. The atmospheric conditions considered were a temperature of -20 °C and a wind relative velocity of 60 m/s. Using the EES Steady-State Model, an external heat convection coefficient of 222.1 W/(m².K) was determined for these conditions. The entire blade was assumed to be at 0 °C at the beginning of the simulation. It is important to note that none of the simulations reached a steady-state condition. The mesh refinement analysis for this model is presented in Appendix L (Section L.3).

Table 5.3: Results obtained in the simulations of the three absorbers in the BMI Model, after 300 seconds

Materials	MWCNT-PP	CCFRP	Eccosorb BSR-1
Maximum MAL Temperature (°C)	125	75.1	74.1
Average MAL Temperature (°C)	45.4	32.3	32.2
Maximum Blade Surface Temperature (°C)	-4.34	0.70	4.89
Average Blade Surface Temperature (°C)	-8.41	-4.69	-1.87
Power Absorbed (W)	209	224	219
Power Absorbed (W/m²)	5214	5596	5465
Absorption Efficiency (%)	52.1	56.0	54.7

MWCNT-PP exhibited a higher MAL temperature, which can be attributed to its lower density compared to the other two absorbers, and similar heat capacity. However, due to its lower thermal conductivity and absorption efficiency, it resulted in a lower blade exterior surface temperature by the end of the simulation. In contrast, Eccosorb BSR-1 showed a lower MAL temperature but achieved the highest blade surface temperature, indicating a shorter heating time. The high density of Eccosorb BSR-1 prevents excessive temperature rise in the MAL, while its lower thickness facilitates faster heat dissipation through conduction to the blade surface.

The highest absorption efficiency in this model was achieved by CCFRP. Nonetheless, all three materials exhibited higher absorption efficiency in this model compared to the previous one. This improvement is primarily attributed to the presence of the lightning protection layer between the MAL and the blade's exterior surface. As detailed in Figure 4.2, in the previous chapter, the introduction of a metallic layer after the MAL significantly reduces microwave transmission through

the absorber, reflecting the radiation back towards the MAL and thereby enhancing absorption efficiency. This effect is visible in Figure 5.5, where the power flow for Eccosorb BSR-1 is shown, which is similar for the other absorbers. It is important to note that, in reality the lightning protection layer is a mesh, rather than a solid metallic layer, and consequently it could still take place some transmission through this layer.

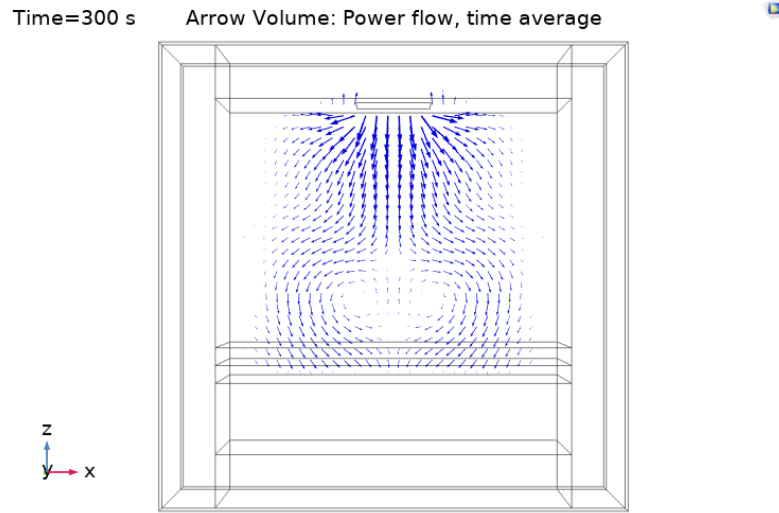


Figure 5.5: BMI Model power flow, for Eccosorb BSR-1. The arrow length is in logarithmic scale to facilitate visualization. The model is represented in the xz -plane.

5.2 2D Airfoil Model

Building upon the previously developed flat plate models, it is important to conduct an analysis using a more complex geometry to obtain more realistic results. However, due to the significant computational effort and extended solving time required for a full 3D model of a wind turbine blade, a 2D cross-section will be employed for further investigation. Although the blade's airfoil profile varies along its length, to simplify the analysis, the airfoil NACA 64-421 was selected due to the reasons explained in Section 4.2.2. The non-stationary results obtained from these 2D models will then be extrapolated to represent the performance across the entire blade.

5.2.1 Constant Convection Coefficient

Simulation Setup

In the initial iteration, the 2D Model utilized a constant convection coefficient (h_{ext}) to simulate heat losses to the exterior airflow. This approach eliminated the need to model airflow around the airfoil, thereby simplifying the modeling process and reducing the solving time.

The airfoil geometry is depicted in Figure 5.6. In this analysis, microwaves are emitted through a waveguide opening with aluminum walls, defined with a port boundary condition. The blade's

layered structure is modeled using the *Layered Material* feature available in COMSOL, while the MAL is modeled as a domain. The blade's materials and thicknesses considered were the ones described in the BMI Model, in Table 5.2. The PML feature is also employed, defined within a rectangular region surrounding the airfoil, as shown in Figure 5.6. The heat transfer analysis is only performed in the blade shell (MAL and blade layered materials).

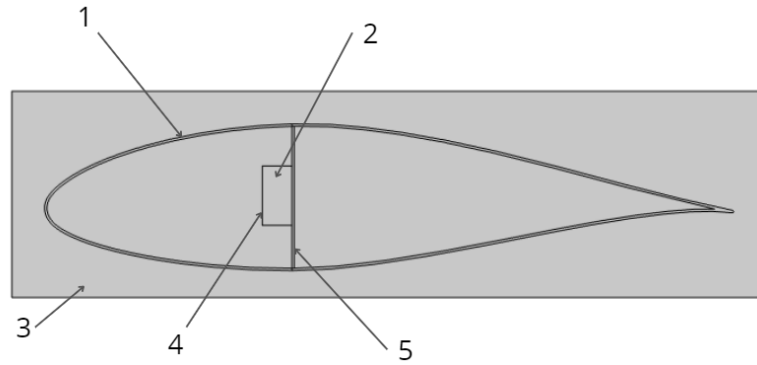


Figure 5.6: Comsol setup of 2D Airfoil Model with constant convection coefficient. 1 - blade shell; 2 - waveguide; 3 - PML; 4 - port; 5 - shear web.

The electric displacement field model was kept the same from the previous models. Internal heat convection is modeled through a heat flux boundary condition, as well as the external heat losses. The multiphysics coupling remains the *Electromagnetic Heating*, and the applied study is also frequency-transient. The mesh refinement analysis is presented in Appendix L (Section L.4).

Results

The results for the three different absorber materials, after 300 seconds of simulation, are presented in Table 5.4. The atmospheric conditions and convection coefficients used (both internal and external), as well as the initial blade temperature, are consistent with those described in the BMI Model. The initial power was considered to be 4000 W/m. Given the airfoil dimensions, if the system hypothetically had 100% of efficiency, this input power would correspond to 5100 W/m² of absorbed power. The selected power could be different, although as in this initial analysis the main interest is to evaluate the absorption efficiencies and the behaviour of the different materials, as long as it is kept constant, excellent insights can be taken. The temperatures, maximum and averages, are only evaluated in the blade region between the shear web and the leading edge, as the rest of the blade is not significantly affected by the anti-icing system. The power absorbed is also presented for this region only, since between the shear web and the trailing edge, power absorption only represents around 0.5% of the total power absorbed.

The absorption efficiencies for all three absorbers increased significantly compared to the previous model. This improvement is attributed to the blade's geometry, which results in reduced losses along the propagation path between the source and the MAL, as well as diminished losses from microwave reflection off the MAL towards the exterior. In this scenario, the majority of

Table 5.4: Results obtained in the simulations of the three absorbers in the 2D Airfoil Model with constant convection coefficient, after 300 seconds

Materials	MWCNT-PP	CCFRP	Eccosorb BSR-1
Maximum MAL Temperature (°C)	152	66.5	86.7
Average MAL Temperature (°C)	43.9	28.5	28.2
Maximum Blade Surface Temperature (°C)	-0.04	0.76	11.3
Average Blade Surface Temperature (°C)	-8.81	-5.03	-3.21
Power Absorbed (W/m)	3891	3954	3892
Power Absorbed (W/m²)	4961	5041	4962
Absorption Efficiency (%)	97.3	98.9	97.3

microwaves reflected by the MAL are reabsorbed by the MAL itself, thanks to the closed curved geometry of the airfoil.

This configuration resulted in changes to the electric field compared to the flat plate models, which in turn affected the reflected and absorbed power for each absorber material. In this model, the highest absorption efficiency was again achieved by CCFRP, consistent with the previous model. The efficiency is not 100% due to microwave energy that was not converted into useful heat and to microwave energy that was slightly absorbed in regions closer to the trailing edge.

Similar to the BMI Model, MWCNT-PP exhibited the highest temperatures within the MAL and the lowest temperatures on the blade surface, for the same reasons previously discussed. Eccosorb BSR-1 achieved a higher blade surface temperature, also aligning with earlier observations, indicating a shorter heating time. However, the superior absorption efficiency of CCFRP led to a more uniform temperature distribution, which is crucial for preventing material overheating within the blade and reducing the disparity between hot and cold spots.

Figure 5.7 illustrates the electric field within the blade and the temperature distribution after 300 seconds, when Eccosorb BSR-1 is used in the MAL. The distribution patterns for the other absorbers are similar, with variations in the magnitude of each parameter. Both figures highlight the leading edge region of the blade, where the microwaves are being emitted and absorbed.

As shown in Figure 5.7b, the temperature distribution is uneven along the airfoil surface. This results from spatial variations in power absorption caused by the electric field, which is not uniform throughout the MAL volume, as illustrated in Figure 5.7a. Figure 5.7b highlights two heating regions in each side of the blade: heating region 1, HR1, near the leading edge, and heating

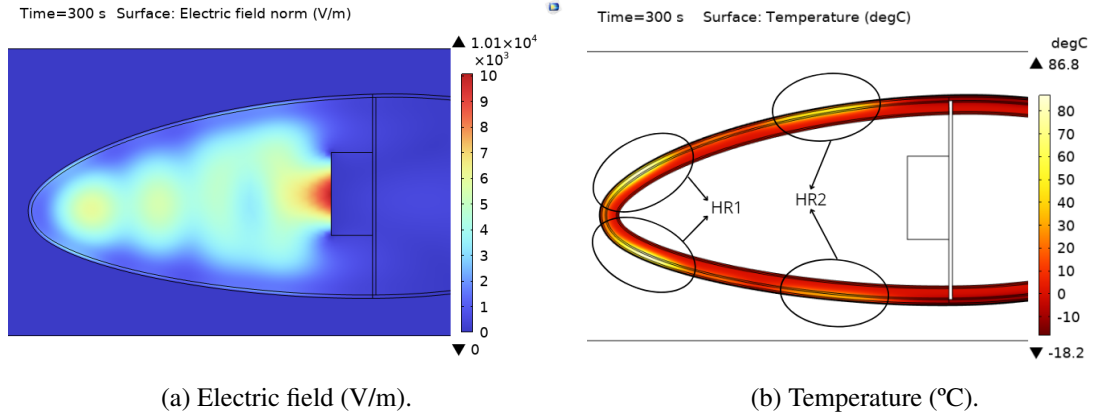


Figure 5.7: Results obtained in COMSOL for the 2D Airfoil Model using constant convection coefficient, for Eccosorb BSR-1, after 300 seconds.

region 2, HR2, closer to the shear web. HR1 has the higher power absorption, and, consequently, maximum temperature.

5.2.2 CFD Simulation

The previous model has some limitations due to the consideration of a constant convection coefficient to simulate the heat losses to the exterior airflow. To overcome this limitation, the airflow was simulated using Computational Fluid Dynamics (CFD) modeling.

This increases the complexity of the simulation, and consequently the solving time. However, it provides valuable insights into the real and accurate effects of the airflow in a wind turbine blade, for specified exterior conditions.

Simulation Setup

The airfoil geometry was modeled similarly to the previous 2D model, using the same airfoil profile and microwave source. The materials remained consistent as well, with the blade's layered materials and the MAL defined as before.

The primary difference in the geometry setup is the addition of a new domain around the airfoil, with significantly larger dimensions to simulate the airflow. This domain consists of a half-circle and a half-square, both centered on the airfoil, with a radius and half-side length that are 50 times greater than the chord length (c) of the airfoil. This geometry is illustrated in Figure 5.8.

To model the fluid flow around the airfoil, it is crucial to determine whether the flow is laminar or turbulent. The transition from laminar to turbulent flow in a fluid boundary layer is generally characterized by the Reynolds number (Re), a dimensionless quantity that represents the ratio between inertial and viscous forces, and is expressed by:

$$Re = \frac{\rho_f \cdot V_f \cdot L}{\mu_f}, \quad (5.1)$$

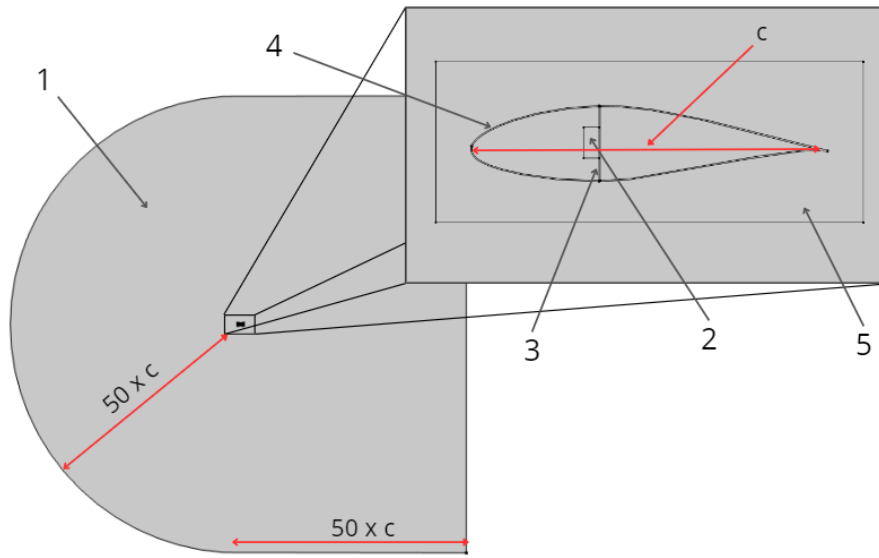


Figure 5.8: Geometry of 2D Airfoil Model with CFD simulation. 1 - airflow domain; 2 - blade shell; 3 - shear web; 4 - waveguide; 5 - PML domain. c is the chord length.

where ρ_f is the fluid density, V_f is the fluid velocity, L is the characteristic length of the flow, and μ_f is the dynamic viscosity of the fluid.

If the flow over an airfoil is simplified to a flow over a flat plate, the critical Reynolds number at which the flow transitions from laminar to turbulent is typically around 5×10^5 . As indicated by equation 5.1, the Reynolds number increases with distance from the leading edge, as the characteristic length for a flat plate is defined as this distance. To determine whether turbulence will occur in the boundary layer, the chord length of the airfoil (1 meter) can be used to calculate the maximum Re value. Additionally, the highest airflow velocity considered in this analysis, 60 m/s, should be used. Using air properties at 20 °C and 1 atm, the resulting Re is approximately 39.9×10^5 . This value indicates that the boundary layer is turbulent in the trailing edge. The exterior airflow outside the boundary layer can be turbulent or laminar, although as we are considering wind in harsh conditions it should be turbulent. Due to the fact that turbulence exists inside the boundary layer and outside of it, a turbulence model was introduced in the simulation.

The *Electromagnetic Waves, Frequency-domain* interface remains unchanged from the previous 2D model. However, an additional interface, *Turbulent Flow*, is introduced to model the airflow. Various turbulence models are available for simulating turbulent flows, and for this study, the Realizable $k-\omega$ model was selected, which is a Reynolds-Averaged Navier-Stokes (RANS) model. This model was chosen for its ability to accurately capture flow characteristics near the blade surface while maintaining computational efficiency.

The flow is assumed to be incompressible, and a No Slip condition is applied to the wall boundary. An Inlet is defined where the airflow enters the air domain, and an Open Boundary is specified where the airflow exits the simulation domain. The air velocity is set within this interface.

The *Heat Transfer in Solids* interface used in previous models is replaced with the *Heat Transfer in Solids and Fluids* interface to account for heat transfer in the airflow. This interface allows

to define the domains which are solid or fluid, so that convective effects can be introduced in the fluid by attributing flow characteristics. The internal losses to the air inside the blade continue to be modeled using a heat flux with a constant convection coefficient, as these losses are primarily due to natural convection and do not significantly influence the heat transfer results within the blade. This is an approximation, as in reality when steady-state is reached in the blade, the internal losses cease to exist, as the inner layer and the internal air will reach thermal equilibrium. Consequently, the heat transfer simulation is only performed on the blade shell and exterior air domains, with the blade defined as solid and the exterior air as fluid.

Additionally, an Inflow and an Open Boundary are included in this interface to set the temperature of the airflow. The selected boundaries to which these conditions are assigned correspond to the same boundaries defined in the *Turbulent Flow* interface for the Inlet and Open Boundary.

In previous models, the only multiphysics coupling employed was *Electromagnetic Heating*. In this model, due to the inclusion of CFD simulation, the *Nonisothermal Flow* multiphysics coupling is added. This coupling allows to simulate fluid flows where the fluid properties depend on temperature, which is not constant. It solves for conservation of energy, mass, and momentum in fluids, coupling the *Heat Transfer in Solids and Fluids* interface with the *Turbulent Flow* interface. A mesh refinement analysis is performed and is shown in Appendix L (Section L.5).

The study conducted is a frequency-transient analysis, similar to the previous models. However, the time-dependent study is initialized with a stationary study for the turbulent flow physics. This approach allows the study to first solve the velocity fields under steady-state conditions, providing consistent initial values for the subsequent transient study.

Results

In this model, defining the airflow around the airfoil requires establishing the angle of attack. For this analysis, an angle of attack of 2.5 degrees was used, as it is a similar value to what Vestas uses, for similar airfoil and atmospheric conditions.

To assess the impact of the CFD approach, the results are compared to those from the previous model, which used a constant convection coefficient to simulate heat losses to the exterior airflow. Using the same power of 4000 W/m and the same airflow characteristics as in the previous model - specifically, an exterior temperature of -20 °C and a wind relative velocity of 60 m/s - the results for the three absorbers are presented in Table 5.5. This analysis, like the previous ones, is conducted over 300 seconds of simulation, with the internal convection coefficient maintained at 1.7 W/(m².K). The blade's initial temperature is also set at 0 °C.

Analysing Table 5.5 and comparing it with the results in Table 5.4, it is visible that the power absorbed and absorption efficiency remained the same as in the previous 2D model. This is because the material properties are unchanged, and the propagation of the electric field remains the same. Consequently, the spatial distributions of the electric field and temperature are similar to those in the previous model, shown in Figure 5.7, featuring the same two heating regions on each surface, HR1 (Heating Region 1) and HR2 (Heating Region 2). The primary difference between this model and the previous one lies in the temperature variation, as the heat losses to the exterior are modeled

Table 5.5: Results obtained in the simulations of the three absorbers in the 2D Airfoil Model with CFD

Materials	MWCNT-PP	CCFRP	Eccosorb BSR-1
Maximum MAL Temperature (°C)	151	64.0	81.9
Average MAL Temperature (°C)	43.2	27.7	27.2
Maximum Blade Surface Temperature (°C)	-4.11	-0.02	4.24
Average Blade Surface Temperature (°C)	-9.54	-6.68	-4.41
Power Absorbed (W/m)	3891	3954	3892
Power Absorbed (W/m ²)	4961	5041	4962
Absorption Efficiency (%)	97.3	98.9	97.3

differently. To facilitate the comprehension of the heat transfer losses to the exterior airflow, the fluid velocity around the airfoil is shown in Figure 5.9.

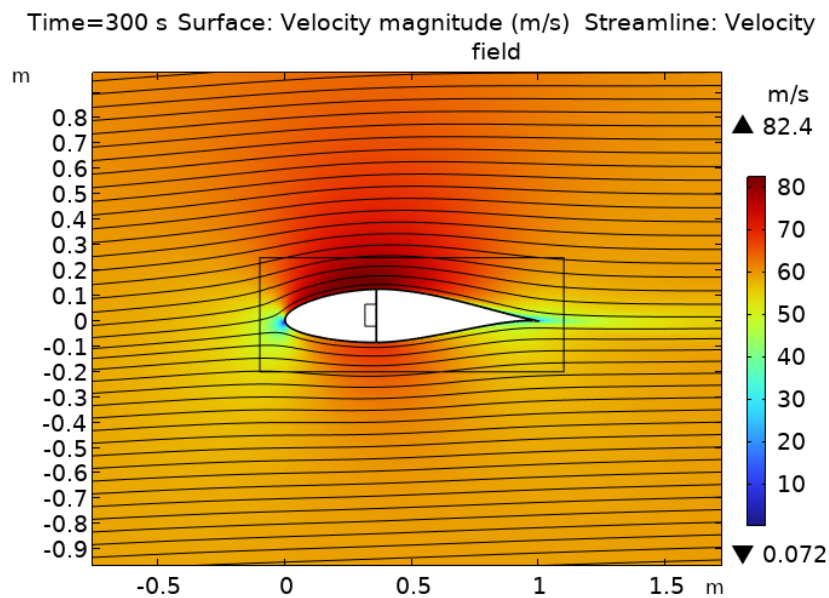


Figure 5.9: Airflow velocity in 2D Airfoil Model with CFD.

The results obtained using CFD indicate lower temperatures - both maximum and average - for the three absorbers, despite using the same power input and achieving the same power absorption. However, for a more thorough comparison, it is essential to examine the variation in external

surface temperature along the 2D cross-section of the blade. Since only the region between the shear web and the leading edge is being heated, the temperature distribution is evaluated along the surface length of this specific section of the airfoil profile. Figure 5.10 represents the arc length used to assess the temperature variation along the surface, denoted as a . The arc length is measured from the point "0", shown in the figure, following the direction indicated by the arrow.

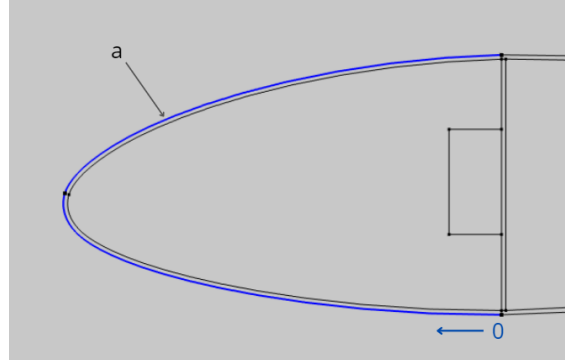


Figure 5.10: Arc length (a) where the temperature distribution along the blade surface is evaluated.

The blade surface temperature distribution along the arc length is presented in Figure 5.11, comparing the two 2D Models with Eccosorb BSR-1 as the absorber. A similar analysis would apply to the other two materials, with the primary difference being the magnitude of the temperatures.

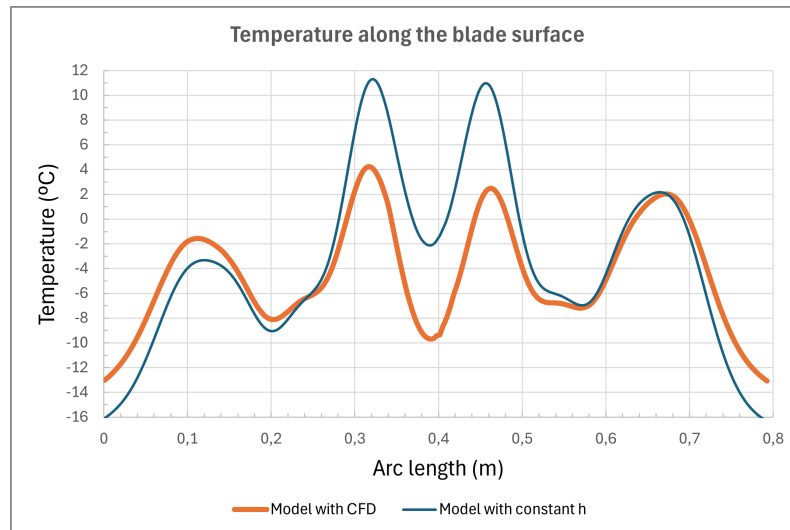


Figure 5.11: Variation of temperature along the blade surface, for the two 2D models.

Figure 5.11 highlights four regions with elevated temperatures corresponding to HR1 and HR2 on both the upper and lower surfaces. It is evident that regions near the leading edge (around 0.4 m along the arc length a) exhibit lower temperatures in the CFD Model compared to the model with constant convection coefficient (h_{ext}), while regions farther from the leading edge display higher temperatures in the CFD Model compared to the constant h_{ext} model.

To understand this variation, it is essential to analyse the heat losses in both models. The previous analysis of the convection coefficient (h_{ext}) becomes more complex due to the velocity distribution shown in Figure 5.9. Previously, h_{ext} was calculated by approximating the airfoil's leading edge as a flat plate. It needs to be taken into account that the convection coefficient generally decreases with distance from the leading edge due to the thickening boundary layer, (see Appendix H).

Furthermore, when calculating the critical h_{ext} for the leading edge using a flat plate approximation, a fluid velocity of 60 m/s was considered. In the CFD Model, the airfoil shape induces higher velocities on the upper and lower surfaces near the leading edge, as seen in Figure 5.9, resulting in greater convection losses in these regions and, consequently, lower temperatures. Since these regions include the heating regions closest to the leading edge (HR1), the maximum temperatures obtained are lower.

In the regions farther from the leading edge, h_{ext} remains constant in the previous model, whereas decreases with distance in the CFD Model, as discussed. Since the heat losses are higher near the leading edge in the CFD Model but decrease with distance, this results in similar temperatures when approaching HR2 (compared to the 2D Model with constant h_{ext}), and even in higher temperatures closer to the shear web, as visible in Figure 5.11. Consequently, the temperature homogeneity is enhanced when developing a more accurate simulation with CFD.

5.3 Comparison of Results with EES Transient Model

To evaluate the reliability of the results obtained from the Blade Materials Integration Model and the 2D Models, a transient model was developed in EES software, to estimate the temperature variations within the blade laminate.

Knowing the blade layered materials and thicknesses, a transient solution can be simplified to observe temperature variation over time, in each layer, until steady-state is reached. This model also allows to simulate different materials and thicknesses for the MAL, as well as different MAL placement in the blade laminate, to visualize the effect of these parameters in heating time. Mathematical formulation and simulation setup of this model is presented in Appendix M.

To simplify, the EES Steady-State model can be used to define the external conditions and equilibrium surface temperature, thereby determining the required power that the MAL needs to absorb and convert into heat. Using this power in the transient model, and considering it constant throughout the MAL volume, along with the previously calculated convection coefficient for the established external conditions, the time to reach the defined equilibrium temperature can be calculated.

For this model, convection coefficient and required power are considered constant and equal to the calculated values for the leading edge region, in the steady-state model. Therefore, the equilibrium surface temperature reached after the transient time is equal to the one defined in the steady-state model.

A comparison was made with the previous models and the results derived from the EES Transient Model under identical conditions. This comparison is only performed for the BMI and the 2D Airfoil Models with constant convection coefficient (h_{ext}), since the EES Model was also implemented with a constant h_{ext} . For the 2D Airfoil Model with CFD Simulation, the power required is different for the same exterior conditions, as detailed in the previous section.

This comparison was conducted for the three selected absorbers, with the respective thicknesses defined in Table 4.2. The exterior conditions considered included a temperature of -20 °C and a wind relative velocity of 60 m/s. Using the EES Steady-State Model, a heat convection coefficient (h_{ext}) of 222.1 W/(m².K) was determined, and the required power to maintain an equilibrium temperature of 5°C on the blade surface was calculated to be 5553 W/m². The initial blade temperature was considered to be 0 °C, and the blade laminate composition was defined according to Table 5.2 and Figure 5.4, similarly to the COMSOL models.

For the BMI Model, the required power was multiplied by the surface area (0.04 m²) to obtain the total power in watts. In the 2D Model, the required power was multiplied by the arc length of the airfoil profile, corresponding to the surface area to be heated, as illustrated in Figure 5.10 and represented by a . This approach ensured that the resulting power in W/m depended only on the dimension normal to the 2D plane. The results of these conversions showed that the power required of 5553 W/m² are equal to 222.12 W and 4355.2 W/m for the BMI Model and the 2D Model, respectively. The input powers required to achieve the desired output (power absorption), using the efficiencies obtained for each model and respective absorber, are presented in Table 5.6.

Table 5.6: Input powers of each model, for the three absorbers under analysis, necessary to achieve the required power absorbed for the specified conditions

Absorber	Input Power	
	Blade Materials Integration Model (W)	2D Model - constant h_{ext} (W/m)
MWCNT-PP	425.97	4477.3
CCFRP	396.96	4405.9
Eccosorb BSR-1	406.44	4476.7

Given that the EES Transient Model assumes a constant power absorption by the MAL throughout the layer volume, the comparison with COMSOL results was based on the average values obtained from COMSOL simulations of the respective layer. This comparison is summarized in Table 5.7. The columns in green represent the blade surface temperatures for each model, while the columns in orange represent the MAL temperatures for each model.

As shown in Table 5.7, despite the temperatures of the BMI and 2D Airfoil Models being average values, the results achieved for each absorber were similar to those obtained with the EES Transient Model.

None of the models reached a steady-state condition, as the transient time required to reach equilibrium, for the given exterior conditions and target blade surface temperature (5 °C), exceeds

Table 5.7: Comparison of blade surface and MAL average temperatures at 300 seconds of simulation

Model	EES Transient		BMI		2D - constant h	
Absorber	Surface T (°C)	MAL T (°C)	Surface T (°C)	MAL T (°C)	Surface T (°C)	MAL T (°C)
MWCNT-PP	-7.90	61.65	-7.78	48.96	-7.74	50.02
CCFRP	-3.97	34.20	-4.78	31.96	-4.62	32.31
Eccosorb BSR-1	-1.14	36.27	-1.62	32.92	-1.52	32.85

the simulation times considered. The temperatures variation throughout 300 seconds of simulation, for the three models compared in this section, are shown in Appendix N.

It is important to highlight that, for this analysis, the power of the anti-icing system is set equal to the power losses at 5 °C on the blade surface, with the goal of achieving an equilibrium temperature of 5 °C. However, if the system's power is higher, the equilibrium temperature will exceed 5 °C, allowing the target temperature to be reached in a shorter time. The heating time is therefore defined as the time required to reach the target temperature (such as 5 °C), but this does not necessarily correspond to the steady-state temperature. This analysis, which depends on the power assigned to the microwave anti-icing system, will be conducted in the next chapter.

Chapter 6

Discussion of System Viability

The previous chapters have laid the foundation for understanding the potential of using microwave energy absorption as an effective anti-icing solution for wind turbine blades. This chapter focuses on the critical analysis of the results obtained from the simplified models and simulations discussed earlier, as well as a comprehensive analysis of the viability of the studied system.

The chapter is organized into several sections. First, the results analysis of the Simplified Blade Models are summarized, followed by an analysis to the system's design, focusing on the microwave absorption by the Microwave Absorbing Layer (MAL), and on the microwave generation and emission system. Following this, the proposed system is verified regarding the established requirements and constraints, examining key metrics such as system power, maximum temperature, and mass. A simplified financial analysis is then conducted to evaluate the investment costs of the system. Finally, the proposed solution is compared with existing anti-icing and de-icing systems, providing a comprehensive overview of its potential advantages and drawbacks.

6.1 Summary of the Analysis to the Simplified Blade Models

In the previous chapter, the results obtained for each model were presented, analysed individually, and compared with those of other models. This section summarizes the development of these models and the analysis of their results.

The Adaptation of Initial Models (Section 5.1.1) focused on comparing the power absorbed across the five flat plate models developed. These models aimed to establish a flat plate model for the MAL, built on the models previously developed and compared with the literature in Chapter 3. Power absorption was prioritized as the key parameter, as it reflects the impact of the sequential modifications in microwave propagation and absorption.

From these five models, a final flat plate model, referred to as the MAL Model, was created to compare the behavior of three selected absorbers in a simplified geometry. This model included only the microwave source and the MAL, surrounded by air. The efficiency observed was relatively low, ranging from 18% to 28% for the different absorbers, due to significant losses to the surrounding air, as discussed in Section 5.1.2.

When the blade materials were integrated into the flat plate in the BMI Model, the results became more representative of real-world conditions, with efficiency increasing to between 52% and 56%. As explained in Section 5.1.3, this increase is largely due to the presence of the metallic lightning protection layer, which reflects microwaves back to the absorber, enhancing efficiency.

This model also introduced a critical aspect of a more realistic approach: heat losses to the exterior airflow (and interior air during transient time) caused by convection. Radiation was excluded from the model, as it was considered negligible in Section 4.3.1. These convective losses are the primary reason for the lower absorber temperatures observed in the BMI Model compared to the MAL Model, despite the higher efficiency.

It is important to note that the thicknesses used in these models correspond to the optimal values calculated using the Reflection Loss (RL) parameter (Table 4.2). However, as discussed in Section 5.1.2, this parameter is only accurate for perpendicular microwave incidence, which was not the case in any of the models. Thus, the optimal thickness of each absorber depends on the specific model. This may explain why CCFRP showed higher efficiency than Eccosorb BSR-1 in the BMI Model but lower efficiency in the MAL Model. Additionally, the presence of the metallic layer introduced reflections that altered the interference patterns of the microwaves, potentially enhancing efficiency in some materials while reducing it in others.

Following the Flat Plate Models, two 2D models of a specific airfoil cross-section of the wind turbine blade were developed: one considering a constant exterior convection coefficient, and the other with CFD modeling to accurately represent the airflow. Both models demonstrated very high absorption efficiencies for the three absorbers, close to 100%, with the most significant differences observed in the temperature distribution along the blade, for the reasons discussed in Section 5.2.2.

These models revealed that the electric field distribution within the blade geometry and materials is not uniform across the airfoil (Figure 5.7), leading to uneven temperature distribution along the MAL and the blade surface. While different airfoil geometries would produce different electric field distributions, this analysis is beyond the scope of this dissertation. The results also showed that changing the absorber material affects these distributions, although similar heating patterns were observed across the three absorbers. The thickness of each absorber also influences these distributions, which will be explored further in the next section.

The comparison between the EES Transient Model, BMI Model, and 2D Airfoil Model with a constant convection coefficient (Section 5.3) indicated that the average temperatures achieved in the COMSOL models were similar to those calculated using EES, reinforcing the validity of the COMSOL models. All three compared models, as well as the 2D Airfoil Model with CFD, demonstrated that using Eccosorb BSR-1 in the MAL resulted in higher blade surface temperatures for the same microwave power and simulation time compared to the other two selected materials.

6.2 Analysis of a System Potential Design

To evaluate the viability of the microwave anti-icing system, it is essential to detail the system's design and define a solution with optimal parameters based on the assumptions considered.

For the subsequent analysis, the microwave system will be examined for a specific design. This approach not only facilitates a discussion on the viability of the technology but also allows for an analysis of the advantages and disadvantages of considering alternative configurations. The system under consideration includes multiple magnetrons installed along the interior of the blade, attached to the shear web, and emitting towards the MAL, as described in Section 4.2.

For simplicity in the analysis, other microwave sources and transport systems discussed throughout this dissertation, such as those in Sections 2.6.1 and 4.2, are not included. Although this choice simplifies the results, most conclusions drawn from this analysis will remain applicable, regardless of the specific system configuration. However, it is important to note that the system's mass, cost, efficiency and reliability would vary with a different design. Potential improvements associated with alternative configurations will also be addressed in this section.

For this analysis, it is assumed that the MAL covers two-thirds of the total blade length, specifically the tip and mid-section regions. This approach is similar to Vestas' current heating resistance anti-icing system, as previously shown in Figure 2.8. The blade length is assumed to be 70 meters.

6.2.1 Microwave Absorption by the MAL

As previously discussed, the MAL is a critical component of the microwave heating system, as it is where the absorption of microwaves and their conversion into heat occurs. In Section 4.4, three materials were selected for further analysis, and Chapter 5 presented the developed models that simulated the system using these three absorbers, allowing for a comparison of the results.

At this stage of the investigation, it is crucial to study the optimal parameters concerning the MAL. This includes analysing the placement of the MAL within the blade laminate and determining the optimal thickness for each absorber to enhance system efficiency. Additionally, it is important to assess the potential impacts that integrating the MAL might have on the blade, both for the studied absorbers and by generalizing the findings to other suitable materials.

6.2.1.1 MAL Placement in the Blade Laminate

The MAL is embedded within the blade laminate, with the specific positioning described in Section 5.1.3, based on the blade's material composition. As shown in Table 5.2 and Figure 5.4, the MAL is placed in layer 5, between two layers of GFRP.

To evaluate whether this positioning is optimal, the EES Transient Model is used to calculate the temperature variation over 900 seconds, with a power input of 5553 W/m^2 (the same power used in Section 5.3 under conditions of -20°C of ambient temperature and 60 m/s of relative wind velocity), for various layer positions of the MAL. Table 6.1 presents the results from this comparison at the end of the simulation period.

Table 6.1 indicates that placing the MAL in layers farther from the blade surface, such as layers 6 and 7, results in longer heating times, as evidenced by lower blade surface temperatures at the end of the simulation. The increased distance that heat must travel from the MAL to the blade

Table 6.1: Comparison of different placements of the MAL within the blade laminate, using EES Transient Model results after 900 seconds

MAL Placement	MAL Temperature (°C)	Blade Surface Temperature (°C)
Layer 5	35.8	4.2
Layer 4	23.5	4.4
Layer 6	71.9	2.3
Layer 7	222.4	-18.1

surface not only extends heating times but also leads to higher MAL temperatures due to greater heat insulation from the higher thickness between the MAL and the surface.

This effect is particularly pronounced when the MAL is positioned in layer 7, where the core layer is situated between the MAL and the surface. The core layer is relatively thick (10 mm) compared to the other layers and has low density and very low thermal conductivity. This causes the core layer to act as an insulator, leading to very high temperatures within the MAL and significantly lower temperatures at the blade surface.

Conversely, moving the MAL to layer 4, closer to the blade surface, produced the opposite effect, resulting in lower MAL temperatures and higher surface temperatures, indicating reduced heating times. Additionally, placing the MAL adjacent to the metallic lightning protective layer (designated SPL) further enhanced absorption efficiency, due to a higher effect of microwave reflection from the SPL back to the MAL. This was confirmed by the 2D Airfoil Model (with constant convection coefficient), which simulated this alternative MAL placement. The absorption efficiency achieved was 98.4%, using Eccosorb BSR-1, slightly higher than the previous 97.3%. In this model, the average MAL and blade surface temperatures were 21.9°C and 4.3°C, respectively, aligning closely with the results presented in Table 6.1.

Nevertheless, the glass fibre layer between the MAL and the SPL is a safety precaution to minimize lightning damage risks to the absorption layer. This risks arise because, when there is a lightning strike, a thermal shock occurs in the adjacent layers to the SPL, which may cause delamination. Therefore, the MAL is positioned at layer 5, with GFRP separating it from the SPL, to protect the anti-icing system. However, extra precautions should be taken with this implementation choice, as the separation between the two layers can result in risks of dielectric breakdown between the two materials, due to voltage differences.

6.2.1.2 MAL Airfoil Positioning

In addition to layer positioning, the MAL can also be integrated into different sections of the blade. The analysis in the previous chapter considered embedding the MAL within the entire airfoil laminate. However, results from Section 5.2 indicate that, for this design, microwave absorption primarily occurs in the region between the shear web and the leading edge. Therefore, the impact of limiting the MAL to this region was studied, as well as the effect of integrating the MAL only in the area between the microwave emission and the leading edge. To investigate these alternatives,

the 2D Airfoil Model with CFD was employed, and the respective MAL placements for these two configurations are illustrated in Figure 6.1.

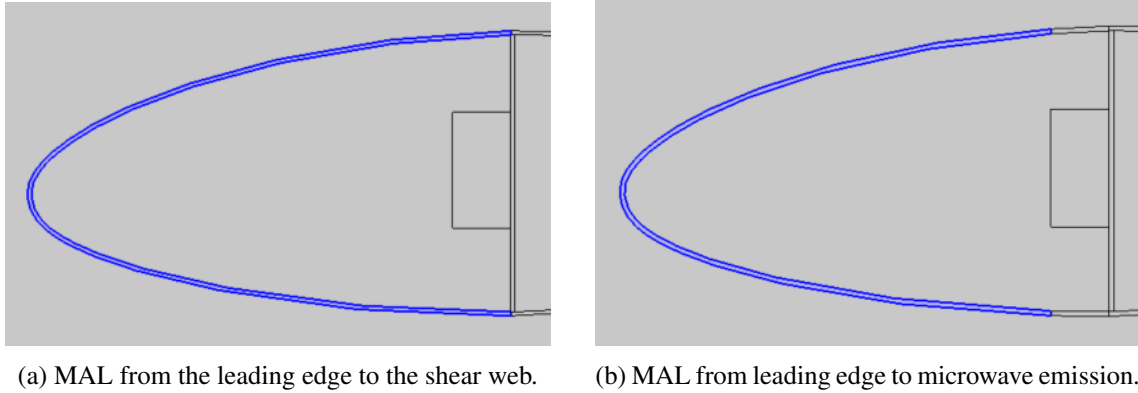


Figure 6.1: Two alternatives for the region of the airfoil where the MAL is embedded in the laminate.

The results obtained in transient regime were compared in terms of temperature distribution along the blade surface. This is considered the most important result to analyse, since it is intended to observe if reducing the region of the blade with the MAL has, or not, negligible impacts on the blade surface temperature. This results are shown in Figure 6.2, at 300 seconds of simulation, considering the arc length illustrated in Figure 5.10.

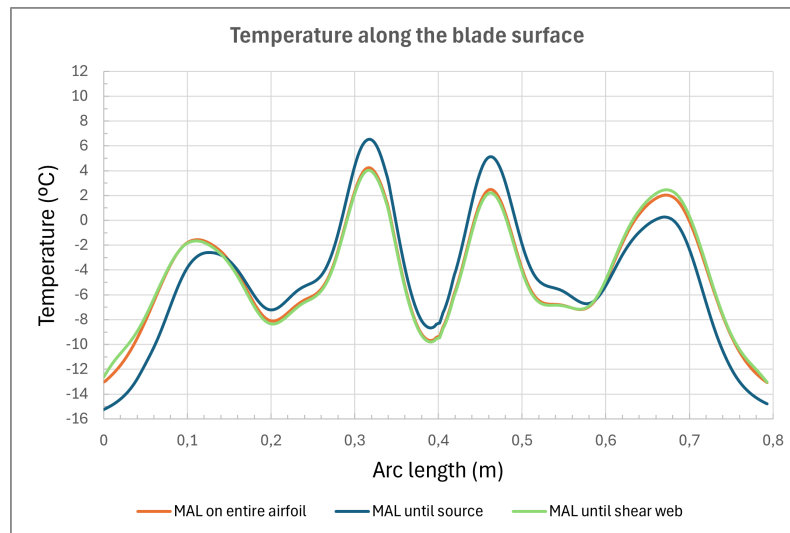


Figure 6.2: Temperature distribution along the blade surface, for the considered arc length (a), for different placement of the MAL.

Figure 6.2 shows that positioning the MAL from the leading edge to the shear web resulted in a temperature distribution nearly identical to that achieved by fully integrating the MAL across the entire airfoil. However, further reducing the region where the MAL is embedded in the laminate led to a significant temperature difference of approximately 2.5 °C in the maximum and minimum temperatures. This increases the non-uniformity of the temperature distribution, leading to more

pronounced differences between hot and cold spots. Therefore, the optimal positioning for the MAL is determined to be in the region between the leading edge and the shear web, embedded in layer 5 of the blade laminate.

6.2.1.3 Optimal Thickness of Each Absorber

The 2D Airfoil Models provided a more realistic representation of the microwave system's behavior inside the blade, even without incorporating the full 3D geometry. The efficiencies obtained exceeded 97% for all three absorbers. However, as discussed in Section 6.1, the thicknesses used for each material were consistent with those in previous models, and an analysis of the optimal thickness for each absorber in the 2D models was not conducted.

To address this, the MAL thickness was varied for each material, and its impact on power absorption efficiency was evaluated. The results of this analysis, obtained with the 2D Airfoil Model with constant h_{ext} , for each absorber, are presented in Figure 6.3.

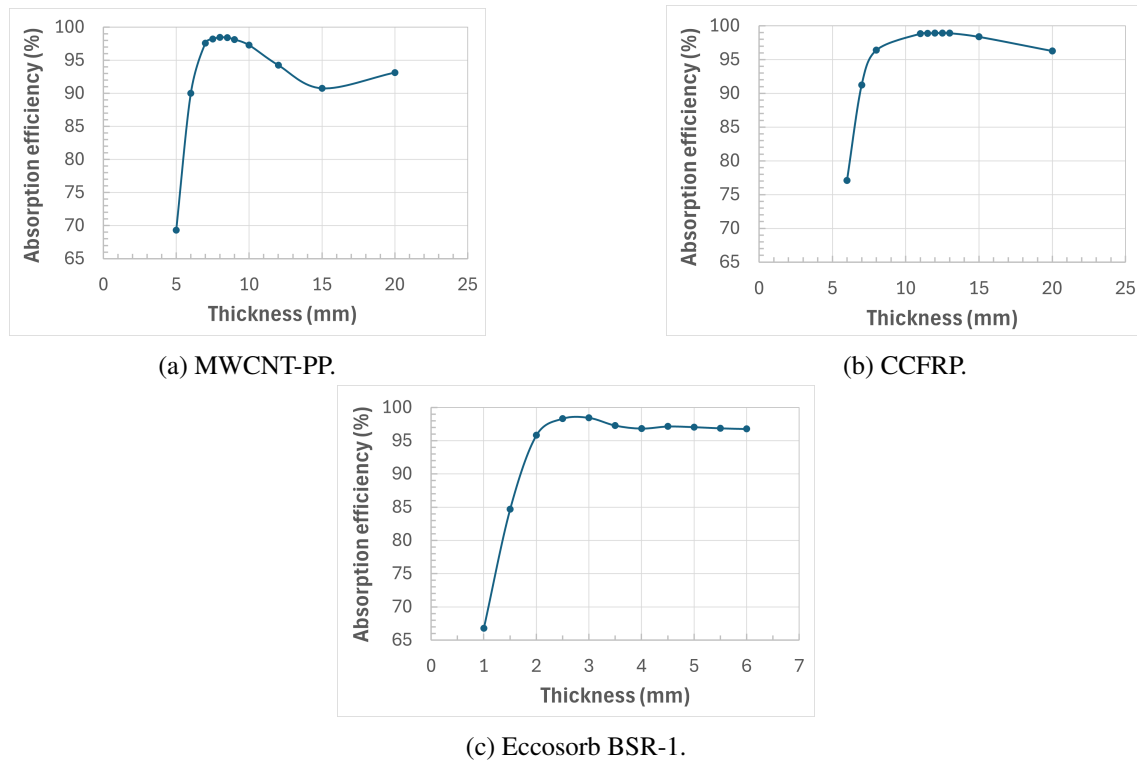


Figure 6.3: Influence of the MAL thickness on power absorption efficiency, for each absorber.

The optimal thicknesses were determined as the values that resulted in the highest power absorption efficiency within the MAL. For MWCNT-PP, CCFRP, and Eccosorb BSR-1, the optimal thicknesses were found to be 8 mm, 12.5 mm, and 3 mm, respectively. With these thicknesses, the absorption efficiencies achieved were 98.5, 98.9, and 98.5, respectively.

6.2.1.4 Mass of Each Absorber

Another critical aspect of the MAL that can significantly impact the feasibility of its integration is the additional mass it introduces to the wind turbine blade. Ideally, the microwave anti-icing system should be designed to maximize efficiency while minimizing weight. As discussed in Section 4.3.2, excessive weight can lead to increased loads, higher vibrations, reduced lifespan, and degradation of aerodynamic performance.

The mass of the MAL depends on the absorber's density and volume. As previously mentioned, the airfoil shape and dimensions vary along the blade's length. To simplify the volume calculation for this analysis, the blade geometry was approximated using a constant cross-section, represented by the NACA 64-421 airfoil used in the 2D Models. Therefore, the surface area that the MAL covers was approximated by multiplying the arc length a , presented in Figure 5.10, by the MAL's length, equal to 2/3 of the 70-meter blade. The MAL volume was then calculated by multiplying the absorber's thickness by the approximated surface area.

Table 6.2 shows the density, MAL volume, and MAL mass, for each of the three absorber materials, using the obtained optimal thicknesses. The lowest mass was obtained with MWCNT-PP and the highest with CCFRP.

Table 6.2: MAL mass calculations for the three absorber materials

Absorber	Optimal Thickness (mm)	Density (kg/m ³)	MAL Volume (m ³)	MAL Mass (kg)
MWCNT-PP	8.0	888	0.29	260
CCFRP	12.5	1223	0.46	560
Eccosorb BSR-1	3.0	4200	0.11	461

6.2.1.5 Risks Analysis

A major concern regarding the design of a wind turbine blade is the vulnerability to lightning damage. Therefore, the blade materials need to be carefully evaluated before its integration, to reduce the risks of lightning. Although an exhaustive study of lightning effects on the MAL is beyond the scope of this dissertation, it is crucial to consider the inherent risks related to the electrical properties of the absorbers.

In the studied design, the MAL is positioned under the lightning protective layer (SPL), with a layer of glass fiber in between, as described in Section 6.2.1.1. Ideally, the SPL should shield the MAL from direct lightning strikes. However, if the MAL is made from a material with high electrical conductivity, it could potentially interfere with the lightning protection system performance, particularly if there is insufficient separation or insulation between the layers. Additionally, even if there is a layer of glass fibre between the MAL and the SPL, induced currents in the MAL can be generated by the SPL in specific conditions, potentially damaging the microwave absorbing material.

Therefore, to avoid potential paths for electrical currents, the MAL would preferably be a poor electrical conductor. From the three considered absorbers, MWCNT-PP and CCFRP demonstrate high electrical conductivity due to the presence of carbon. In contrast, Eccosorb BSR-1 is electrically non-conductive, with its microwave absorption capabilities primarily derived from its high magnetic loss. This non-conductive property may offer an advantage over the other two materials in terms of reducing lightning-related risks. A full investigation, with a deep research analysis, multiphysics simulations, and experimental tests, should be performed to evaluate accurately the risks of lightning in the MAL for different materials.

Another critical characteristic of the MAL material that must be considered is its durability. As discussed in Section 4.3.2, to avoid premature failure and the need for replacement, the MAL should be durable enough to last throughout the wind turbine's expected lifetime. Although maintenance is possible in the event of damage to the MAL, it should be minimized as much as possible, since performing maintenance on wind turbines in cold climates is a highly challenging operation.

The durability of a material depends on various factors, including the operational conditions of the wind turbine, the mechanical stresses that the blade materials are subjected, the environmental conditions, the manufacturing processes, material compatibility with other components of the blade, and the material's intrinsic properties, such as mechanical strength and fatigue resistance. Therefore, to accurately assess the lifespan of the specific materials studied in this dissertation, it would be necessary to conduct specific experimental tests and undertake an exhaustive study of their properties. However, such an in-depth evaluation is beyond the scope of this dissertation.

6.2.1.6 Selection of MAL Material

It is important to reiterate that identifying the best available MAL material was not an objective of this dissertation. As explained in Section 4.4, the purpose of studying the MAL materials was to characterize a few potential options to evaluate the viability of this ice protection system. By choosing the most suitable material from the materials selected initially, identified through extensive research as potentially excellent microwave absorbers, the potential of this technology can be discussed. Future investigations on the ideal MAL material could obtain even better results than those presented in this analysis.

Given the analysis developed in this section, the selected absorber material for the microwave anti-icing system is the Eccosorb BSR-1. It is important to remember that this material and the respective properties were obtained from a supplier. Some parameters for the selection of the most suitable absorber were established:

- The results presented in the previous chapter for the EES Transient Model, BMI Model, and 2D Airfoil Models demonstrate that this material led to shorter heating times for the blade surface compared to the other absorbers;
- Its optimal thickness is the lower value of the three materials, allowing to obtain similar power absorption efficiency, around 98.5 %, with less thickness (38% and 24% of the MWCNT-PP and CCFRP thicknesses, respectively);

- Despite its high density, the low thickness of this material resulted in a lower mass than CCFRP. MWCNT-PP is even lighter, although, among the three materials considered, it performed the worst in terms of absorption efficiency and heating time, and it also exhibited the highest MAL temperature, as shown in the results from the previous chapter;
- Eccosorb BSR-1 is the only non-electrical conductor material of the three, which may facilitate its integration with the lightning protection layer.

Other parameters could have been taken into account, such as heat distribution, maximum temperature, or even the cost of the raw material. However, it was prioritized the efficiency, heating times, integration in the blade, and total weight. This material's excellent microwave absorption capabilities are primarily due to its outstanding magnetic loss, which is attributed to a high value of the imaginary part of permeability (μ_r'').

It is important to emphasize that this analysis, along with the selection of absorbers, is only conducted for a frequency of 2.45 GHz. For different frequencies, the materials' electromagnetic properties change, potentially leading to different conclusions. Optimizing the operating frequency could result in even higher absorption efficiencies with these or other microwave absorbing materials.

While the power absorption efficiency is already near 100% at 2.45 GHz for these materials, improvements could be made in achieving a more uniform power absorption, leading to a more homogeneous temperature distribution within the MAL. Additionally, at different frequencies, some materials may exhibit higher attenuation (α) and lower penetration depth (D_p), as discussed in Section A.3.1. This could allow for the use of even thinner MAL layers.

Moreover, the thermal properties of Eccosorb BSR-1 are not ideal, as it has a very high density and low thermal conductivity. A material with a lower density would reduce the overall mass for the same volume, and a higher thermal conductivity would decrease heating times and lower the maximum MAL temperature.

6.2.2 Microwave Generation and Emission

After discussing the absorption component of the microwave anti-icing system, it is crucial to analyse the microwave generation and emission aspects of the system. As mentioned earlier in this section, the design under consideration involves multiple magnetrons positioned along the blade interior, attached to the shear web, and emitting microwaves towards the MAL.

This consideration allows to discuss the viability of the system and its optimal parameters, as well as the potential improvements obtained with alternative designs, described in Section 4.2.

6.2.2.1 Maximum Spacing Between Sources

If microwave sources are placed sequentially inside the blade, it is crucial to determine both the number of sources and the power output of each. A key parameter that constrains the number of sources is the maximum spacing between them. This parameter is critical because a single

microwave generator cannot uniformly emit electromagnetic energy across the entire volume of the MAL. Instead, each section of the blade is heated by a specific microwave source, necessitating the definition of the maximum section each source can effectively heat, or in other words, the maximum spacing between adjacent magnetrons.

Given that a full 3D model of a microwave anti-icing system inside a wind turbine blade is beyond the scope of this work, simulating multiple microwave sources within the blade is not feasible. To approximate the maximum spacing between sources that still ensures effective microwave propagation along the entire blade length, the MAL Model was utilized. While this approach has clear limitations, as the flat plate is a highly simplified geometry, it provides an initial estimation, although the actual value of this parameter in a more complex geometry might differ.

The flat plate model was simulated in COMSOL for three different lengths: 0.2 m, 0.5 m, and 1 m. The power loss distribution for each length is provided in Appendix O. The results indicate that microwave power is effectively absorbed only for lengths up to 0.5 m. Therefore, it is assumed that 0.5 m is the maximum spacing between adjacent sources. Beyond this distance, microwave absorption may not cover the entire length of the MAL, potentially leading to cold spots and an increased risk of icing.

6.2.2.2 Optimal Number of Microwave Sources

To determine the optimal number of sources for the microwave anti-icing system, several factors must be carefully considered. One key point is that as the number of microwave sources inside the blade increases, the power required from each source decreases, and vice-versa. Therefore, the initial step is to establish the power per source needed for a given number of sources.

The power requirement for each source will also depend on the specific airflow conditions, particularly the ambient temperature and relative wind velocity. These factors influence the rate of heat loss from the blade surface, thereby affecting the overall power needed to maintain effective heating. Other factors such as liquid water content (LWC) of air and median volume diameter (MVD) of droplets, see Section 2.3, impact ice formation and the heating power requirements, although these factors were not considered throughout this dissertation.

For this analysis, some assumptions were made:

- To calculate the surface area to be heated, a constant cross-section area along the blade was considered, using the dimensions of airfoil NACA 64-421;
- As previously mentioned, the blade length is assumed to be 70 meters, with the MAL integrated along only two-thirds of this total length, starting from the tip;
- Eccosorb BSR-1 is considered for the MAL, since it was selected as the most suitable absorber, with its optimal thickness of 3 mm;
- The power required is calculated using the EES Steady-State Model, considering an equilibrium surface temperature of 5 °C. This value is calculated for the leading edge, although it was assumed constant throughout the whole blade surface area to be heated;

- It is disregarded any microwave interference between adjacent sources, which could affect the absorption efficiency.

Figure 6.4 shows the variation in power required per microwave source with the increase in the number of sources per blade (from 33 to 733 magnetrons), for different airflow conditions (ambient temperature and relative wind velocity), considering the enumerated assumptions.

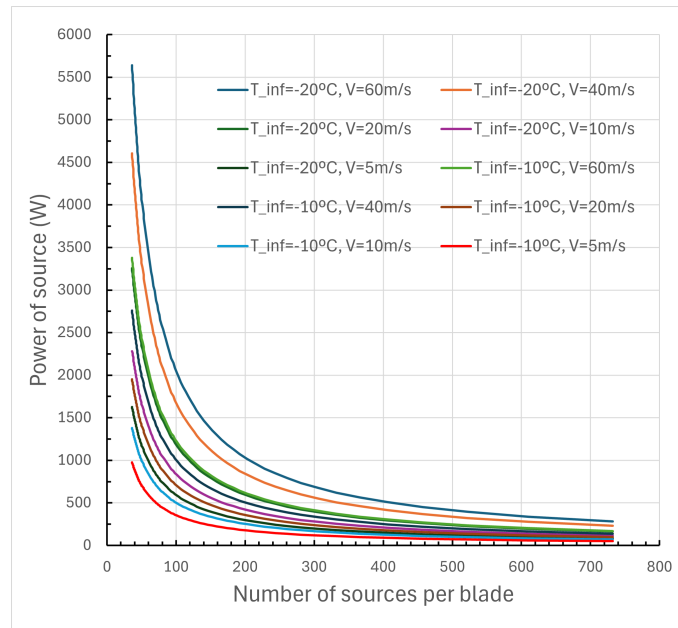


Figure 6.4: Variation of power required per microwave generation unit with number of units, for different ambient temperatures and relative wind velocity.

This analysis shows that the power of each magnetron is highly dependent on the number of sources inside the blade and on the airflow conditions. The minimum number of magnetrons that can be used inside the blade is established by the maximum spacing between sources, discussed in this section, which results in a minimum of 90 magnetrons (length of the MAL divided by the maximum spacing between sources).

After establishing this minimum number, it is essential to decide whether it is advantageous to maintain the number of magnetrons close to this limit, or to increase the number of units by reducing the power output of each source. Several factors must be considered for this decision, such as reliability, flexibility, costs, weight, and redundancy.

For the purpose of this work, it is considered that having less magnetrons inside the blade is beneficial, despite the increased impact of a component failure and reduced system flexibility. This conclusion is based on the fact that the maximum spacing between magnetrons is only 0.5 meters. Since half a meter does not allow for significant variations in wind relative velocity, the power requirements for adjacent sources are likely to be similar. Therefore, this distance is sufficient to provide a flexible system that can adjust the power distribution from the blade root to the tip. Additionally, reducing the number of magnetrons offers several advantages, including lowering

the system's mass, reducing costs, simplifying the electrical system, and minimizing potential failure points. Therefore, an optimal number of 90 magnetrons is selected.

Further analysis of the power requirements for each magnetron unit will be conducted in Section 6.3.1, considering the varying power demands across different sections of the blade under critical conditions.

6.2.2.3 Analysis to the Microwaves Emission Method

The 2D Models of the airfoil considered microwave emission through a waveguide (WR-340) opening. While the modeling and simulation of more complex designs for microwave emission fall outside the scope of this dissertation, it is important to acknowledge that employing more advanced emission mechanisms, such as antennas, could potentially enhance microwave absorption and result in a more uniform power distribution within the MAL volume.

As mentioned in Section 4.2, horn antennas have demonstrated in some studies to be highly effective in achieving the desired energy absorption inside the blade. However, incorporating these components into the 2D Models would require an in-depth study of optimal geometry and boundary conditions.

Furthermore, in this dissertation, the microwaves are assumed to be emitted from a component attached to the shear web. The shear web's location inside the blade varies depending on the specific airfoil design. Some configurations position the shear web farther from the leading edge, while others include two webs within the blade. In such cases, microwave emission could occur farther from the leading edge, potentially leading to different conclusions, as the power absorption might be distributed over a larger area of the blade surface.

6.2.2.4 Possible Limitations

Regarding the microwave generation and emission system, if the configuration described in this chapter is chosen, there are several aspects that would require further analysis and testing. If the magnetrons are placed along the blade and attached to the shear web, the lifespan of this components could be critical. An industrial magnetron is expected to work without failure from 5000 to 10000 hours, as mentioned in Section 2.6.1 [52, 56].

Given this lifespan, depending on the number of hours the ice protection system operates annually, the magnetrons might need to be replaced before the wind turbine reaches the end of its service life. For instance, if the anti-icing system is active for 300 hours per year, the magnetron's lifespan could range from 17 to 33 years (depending on the lower and upper limits considered for the magnetron's durability). For this scenario, the magnetrons would likely do not require replacement. On the other hand, considering a cold climate with longer harsh conditions, the anti-icing system could be expected to work several more hours. For example, considering a scenario with three winter months, and system activation of 12 hours a day, the magnetron's lifespan would range between 5 and 9 years. Even more demanding climates would require magnetrons replacement multiple times in the wind turbine's lifetime.

Despite this replacement being achievable, it should be avoided if possible, since performing maintenance on wind turbines in cold climates is a highly challenging operation, as previously mentioned.

One potential solution to this problem is the use of solid-state generators instead of magnetrons, as solid-state generators have considerably longer lifespans, as discussed in Section 2.6.1. Additionally, solid-state generators offer other advantages, such as finer frequency control and enhanced power regulation, which are also detailed in the mentioned section.

Alternatively, positioning the microwave sources at the root of the blade or inside the hub, with microwave transmission and emission through waveguides, could simplify maintenance by making the sources more accessible.

6.3 Verification of Requirements and Constraints

This section aims to verify whether the system's requirements have been met while respecting the established constraints. In this analysis, the primary goal of the anti-icing system is to achieve a blade surface temperature of 5 °C. As discussed in Section 5.2, the 2D Model results indicated that the temperature distribution along the blade surface is not uniform due to the non-homogeneous power loss distribution caused by the electric field pattern inside the blade. Therefore, this analysis considers the system's objective fulfilled if the average blade surface temperature reaches 5 °C.

Maintaining a 5 °C margin above the freezing point (0 °C) is assumed to ensure the system's reliability. Achieving this average temperature is crucial for two reasons:

- The non-uniform temperature distribution results in hot and cold spots along the blade surface. By targeting an average temperature 5°C above freezing, the system is more likely to achieve higher temperatures in the hot spots and minimize, or ideally eliminate, areas where the temperature might drop below 0 °C;
- The models used might underestimate the actual power losses to the exterior or overestimate the power absorbed by the MAL. The 5 °C margin acts as a precaution to account for any potential inaccuracies, ensuring the system effectiveness under real operating conditions.

6.3.1 System Power

6.3.1.1 Power Estimation

The power required from the anti-icing system to heat the blade is not affected by the heating method implemented. It depends on the exterior conditions of the airflow, geometry and dimensions of the blade. Therefore, the power supply needed for different heating methods depends solely on the efficiency with which each method converts electrical energy (or other forms of energy) into useful heat. A comparison of the efficiency between the microwave system and the current anti-icing system will be discussed in the next section.

It is also important to reiterate that the power required to heat the blade is not uniformly distributed along its length. The heating power needed near the blade's tip is significantly higher

than near the root, primarily due to the higher relative wind velocities. Therefore, it becomes complex to accurately calculate the total power requirement for the whole blade.

Since this dissertation does not include any 3D model of a full wind turbine blade, to evaluate the system's power in a simplified approach, the region of the blade affected by the MAL was divided in five sections - A (near the tip), B, C, D and E - showed in Appendix P, and for each section it was attributed specific external conditions to the airflow. The critical conditions assumed for this analysis were an ambient temperature (T_{∞}) of -20°C , a blade rotational speed (ω_r) of 8 RPM, and a wind upstream velocity (V_o) of 20 m/s. With these values, the critical conditions for each section can be determined, with varying wind relative velocities.

The power required to maintain a steady-state blade surface temperature (T_{sup}) of at least 5°C , as a function of wind relative velocity, was estimated using the EES Steady-State Model and is presented in Figure 4.5. Using these results, the power requirement for each section was determined based on the corresponding relative wind velocity. The complete process to obtain the critical conditions as well as the maximum power per magnetron for each section, is described in Appendix P. Given the mentioned assumptions and the process described in Appendix P, the microwave system would require:

- 18 magnetrons of at least 2.26 kW each, for region A (blade tip)
- 18 magnetrons of at least 2.12 kW each, for region B
- 18 magnetrons of at least 1.96 kW each, for region C
- 18 magnetrons of at least 1.81 kW each, for region D
- 18 magnetrons of at least 1.65 kW each, for region E

As seen in section 4.3.2, the maximum power available for each blade, if the system is working in anti-icing mode, is 93.33 kW. This simplified approach resulted in a total power of 176.3 kW for the considered critical conditions, which is considerably higher.

It is important to emphasize that these results are expected, as current anti-icing technologies are also not designed to operate under the most extreme conditions. The conditions considered in this analysis are exceptionally harsh, and in such cases, wind turbines typically interrupt operation and undergo de-icing using power from the grid.

The operation and power requirements of the system will depend heavily on ice formation prediction and control systems. These systems determine whether the anti-icing system is activated based on external conditions such as ambient temperature, wind relative velocity, liquid water content (LWC) of the air, and the median volume diameter (MVD) of droplets. These factors influence the likelihood and severity of icing events, and thus the activation and power needs of the anti-icing system. However, the study of these control systems, along with the impact of LWC and MVD, is beyond the scope of this dissertation.

Some alternative scenarios were explored to understand the conditions under which the system might still function effectively. Using the same approach as described in Appendix P, the power requirements for the microwave anti-icing system were estimated based on five other different

scenarios. Table 6.3 shows the results obtained, with the first scenario corresponding to the critical conditions considered above. The maximum power per source represents the power supply per source in region A (18 sources located at the tip of the blade).

Table 6.3: Power requirements for different scenarios

Scenario	1	2	3	4	5	6
Target for T_{sup} (°C)	5	5	5	5	3	3
ω_r (RPM)	8	8	8	7	8	7
T_∞ (°C)	-20	-10	-8	-10	-10	-15
V_o (m/s)	20	10	10	10	20	5
Max. Power per source (kW)	2.26	1.32	1.15	1.24	1.17	1.48
Total Power (kW)	176	101	87	93	92	112

Analysing Table 6.3 it is evident that the microwave anti-icing system can successfully reach the blade surface target temperature in scenarios 3, 4 and 5. It can be concluded that the ambient temperature has a higher effect than the wind upstream velocity, and that considering lower target surface temperatures can also result in a considerable decrease in total power.

6.3.1.2 Heating Times

The heating times required for the microwave anti-icing system to heat the blade surface are crucial for characterizing the developed system and can be estimated based on several factors. These factors include the power absorbed by the MAL, the target blade surface temperature, and the airflow conditions - specifically ambient temperature and relative wind velocity.

Using the EES Transient Model, the heating times needed to reach a blade surface temperature of 5°C were calculated for various airflow conditions and power absorption levels in the MAL. Figures 6.5 and 6.6 show the results obtained for ambient temperatures of -10 °C and -20 °C, respectively. The blade initial temperature was considered to be 0 °C for all materials.

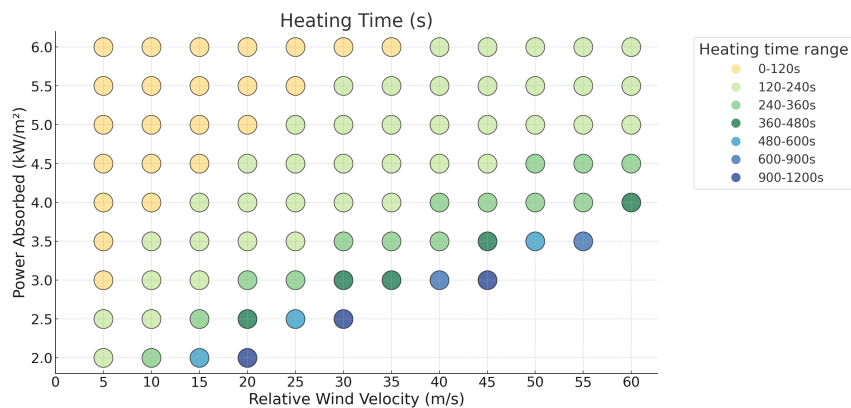


Figure 6.5: Heating times to reach 5 °C, calculated with the EES Transient Model, using 3mm of Eccosorb BSR-1 in the MAL, for ambient temperature of -10 °C.

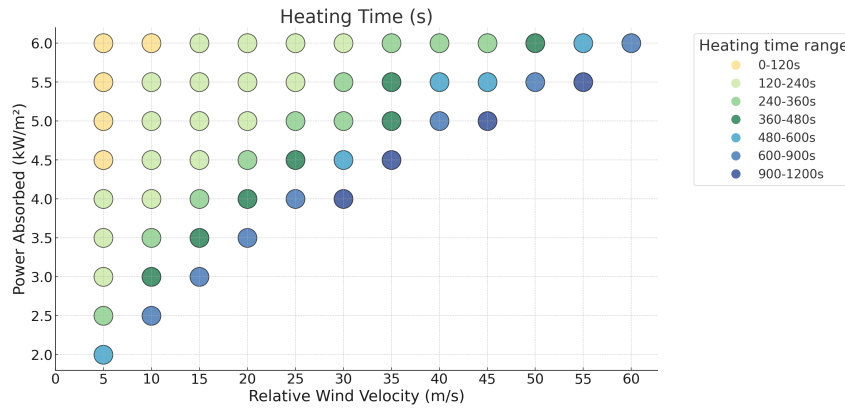


Figure 6.6: Heating times to reach 5 °C, calculated with the EES Transient Model, using 3mm of Eccosorb BSR-1 in the MAL, for ambient temperature of -20 °C.

The heating times indicate that under critical exterior conditions, it is challenging to reach a blade surface temperature of 5°C within the power range considered in this analysis. However, for harsh atmospheric conditions that are less severe than the critical values, rapid heating can be achieved, as indicated by the yellow and light green circles (representing heating times below 120 and 240 seconds, respectively).

The power absorption range considered in this analysis is 2 to 6 kW/m², which can be correlated with the power of an individual magnetron. For instance, using the previously defined number of magnetrons for region A, to achieve the maximum power absorption of 6 kW/m², each magnetron would need to operate at 2.5 kW. This power level is commonly available for magnetrons, suggesting that using even higher powers could be advantageous under critical exterior conditions. However, these higher power levels may not be available to the anti-icing system, as seen in the previous section.

Additionally, in this analysis the initial temperature of all the layers that compose the blade shell was set to 0 °C. In an anti-icing system with precise control, the heating system is activated when there are icing conditions, preventing the temperature from reaching the freezing point. Therefore, the initial temperatures inside the laminate are higher than those considered in this analysis, which reduces the heating times.

6.3.2 System Temperature

The maximum temperature allowable in the blade is 55 °C, as established in Section 4.3.2. To evaluate this constraint, it is necessary to calculate the maximum temperature the blade could reach. This evaluation was performed in the tip of the blade, where the power absorbed in the MAL is maximum. This maximum temperature can be estimated using the 2D Airfoil Model with CFD, simulating the critical exterior conditions specific to the blade tip defined for region A in the previous section. It is important to note that this is an approximation, as the tip airfoil differs from the one used in this model, which is more representative of mid-blade sections.

As detailed in Appendix P, the critical conditions for region A are: an ambient temperature of -20°C and a relative wind velocity of 58.3 m/s . These airflow conditions are introduced into the 2D CFD Model, along with the MAL configured with the defined optimal characteristics: 3 mm of Eccosorb BSR-1, extending from the leading edge to the shear web, positioned in layer 5. The angle of attack is kept at 2.5 degrees.

As seen in the previous section, the power required for each magnetron in region A is 2.26 kW for the critical scenario. This corresponds to a power supply of 4360 W/m (depending on the dimension perpendicular to the 2D cross-section) or an absorbed power of 5473 W/m^2 . However, a detailed examination of Figure 6.6, reveals that under these critical conditions - where the absorbed power is near 5.5 kW/m^2 and the relative wind velocity ranges between 55 and 60 m/s - the resulting heating times would be excessive, exceeding 20 minutes. Therefore, to obtain a more viable heating time, under 10 minutes, the absorbed power target is set at 6 kW/m^2 .

To determine the input power for the COMSOL model, this target power is multiplied by the arc length a , and then divided by the MAL's absorption efficiency, resulting in a power of 4.78 kW/m . Figure 6.7 shows the electric field and temperature obtained for the optimized system, at 600 seconds of simulation time in transient regime, and under the conditions specified above.

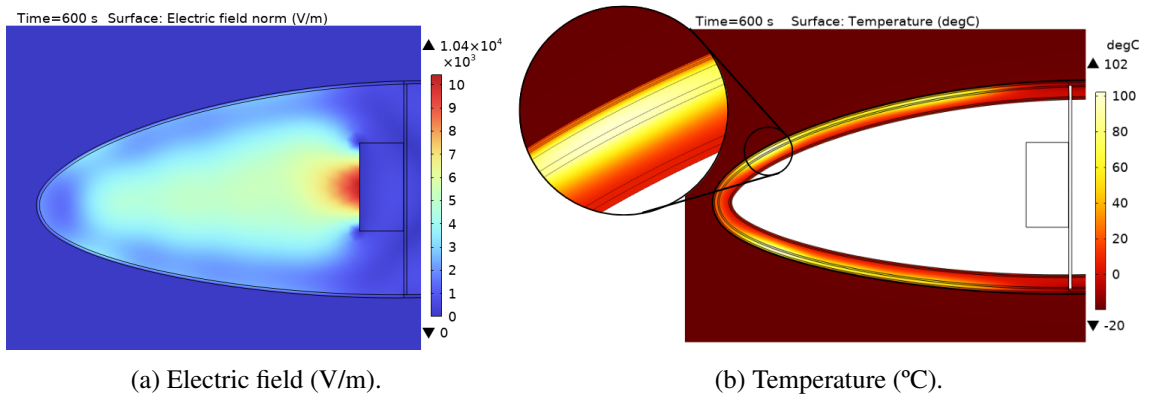


Figure 6.7: Results obtained in COMSOL for the 2D Airfoil CFD Model, with optimized parameters, for 600 seconds of simulation time.

The first observation from these results is the improved uniformity of the temperature distribution along the blade. For this optimized MAL configuration, the absorbed power was considerably more homogeneous throughout the absorber, resulting from a more even distribution of the electric field within the airfoil. If less severe conditions than the critical values were considered, like scenarios 2 to 6 from Table 6.3, the overall temperature magnitudes would be lower, but the same homogeneous temperature distribution would be achieved, as it primarily depends on the power absorbed within the MAL. For the given conditions and power, the variation in blade surface temperature along the arc length a is shown in Figure 6.8.

As visible in Figure 6.8, the temperature remained below 0°C only at the leading edge and in the regions near the shear web. In the heating regions between the leading edge and the shear web, the surface temperature exceeded 5°C , reaching a maximum of 12.4°C .

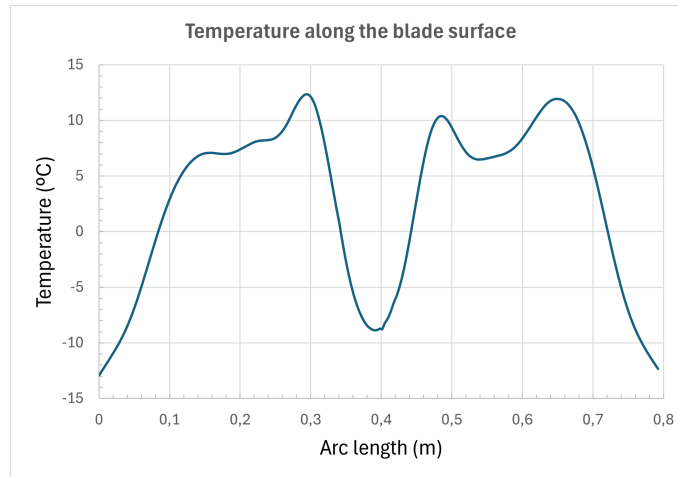


Figure 6.8: Temperature distribution along the blade surface, after 10 minutes, for the considered arc length (a), for the critical conditions and a power of 4.78 kW/m.

For this power, the MAL reached a maximum temperature of 100 °C, which is considerably higher than the 55 °C maximum allowable temperature. However, this high value is reached in a region without adhesive material, which as seen in Section 5.1.3, is only present in the leading edge and near the shear webs, precisely where the blade temperature is lower. It should still be considered that the polymeric matrix of composite materials, such as GFRP, could also be impacted by the high temperatures achieved.

This simulation is performed for the critical conditions, which, as seen in the previous section, requires a higher power than the available for the anti-icing system. If a feasible power is used for a valid scenario, than the maximum temperature reached in the blade will be lower. For example, using the conditions described in scenario 3 from Table 6.3, a total power of 2.77 kW/m² for region A is required. Similarly to the approach for the critical scenario, a higher power is targeted to reduce heating times, equal to 3kW/m² which is half of the previously considered power. Simulating in COMSOL using the 2D Airfoil Model with CFD, with these conditions for scenario 3 and a total simulation time of 10 minutes, it is possible to estimate the temperatures reached by the blade materials in a realistic application of the anti-icing system.

The results obtained after simulation show that the maximum temperature reached for these conditions is 53 °C. This value is lower than the maximum allowable temperature in the blade, showing that under conditions that the microwave anti-icing system can operate, the temperature constraint can be respected. The maximum and averages temperatures of the blade surface reached in this simulation were 8.6 °C and 3.9 °C, respectively.

It must be highlighted that the temperature distribution would change with the airfoil considered. Adding to this, the MAL material is crucial to the temperature variation inside the blade, and a material with a higher thermal conductivity would result in a lower temperature inside the MAL, which could be beneficial for thermal stability of the blade materials. For Eccosorb BSR-1, the maximum allowable operating temperature is 170 °C, so reaching temperatures around 100 °C does not pose risks to the material's integrity. It is also important to note that only the heat gener-

ated in the MAL is being considered, while in reality there could be heat losses in the magnetron affecting blade materials. However, magnetron's cooling systems will limit its temperature rise.

6.3.3 System's Mass

As discussed in Section 6.2.1, the microwave anti-icing system should be designed to maximize efficiency while minimizing weight, due to a variety of factors already discussed. After selecting the MAL material and estimating its mass, it is essential to include the entire microwave system.

For the chosen design, in addition to the MAL mass, the weight of the magnetrons must also be considered. Currently, magnetrons on the market, operating at a frequency of 2.45 GHz and within the power range considered, can weigh between 1 and 5 kg each. Considering a total number of 90 magnetrons, the system's weight can be estimated within a minimum and maximum range.

The minimum additional mass contributed by the 90 magnetrons is 90 kg, while the maximum is 450 kg. When this is combined with the MAL weight, the total mass of the microwave anti-icing system per blade is estimated to be between 551 kg and 911 kg. It is important to note that the selected absorber has a very high density. Therefore, choosing a lightweight microwave absorbing material could result in a significantly lower weight. Additionally, this estimation does not account for all the necessary additional equipment which could increase considerably the system's total mass. Given that a 70 m blade can weigh more than 20 tons, this estimation results in a mass increase of less than 3% to 5%.

6.4 Financial Analysis

This section presents a simplified financial analysis of the proposed microwave anti-icing system for wind turbine blades, focusing on the estimation of the Capital Expenditure (CAPEX).

The financial benefits of an anti-icing system are primarily derived from the reduction in down-time due to icing. For the microwave anti-icing system, this reduction will be comparable to the currently implemented anti-icing systems if the system prevents icing with the same efficiency. Additionally, since the anti-icing system operates using the wind turbine's own energy production while in rotation, no additional energy costs are incurred during operation. Therefore, analysis of this system's economic viability will be performed by analysing the investment costs.

There are other factors that can influence the economical viability compared to the current used anti-icing systems. If the electrical energy required to perform is less than those from other technologies, the energy savings with this system could be higher. Adding to this, if the manufacturing of these systems is simplified, not only the investment costs could be lower, but also the time and resources required to manufacture the anti-icing systems would be reduced. Another factor that can influence the economical viability is the operational costs throughout the wind turbine lifetime (OPEX), which are not analysed in this section.

To obtain other financial metrics, the payback period and ROI (return on investment) could be estimated. However, this would require a more in-depth analysis, taking into account the OPEX, inflation, debt amortization, and annual savings, which is beyond the scope of this project.

The CAPEX primarily includes the cost of the MAL, magnetrons, auxiliary equipment, and installation. The MAL, composed of Eccosorb BSR-1, is a significant cost component priced at approximately €950 per square meter for a thickness of 3 mm, based on supplier information. Given that the MAL covers 2/3 of a 70 m blade, with a surface area of 36.6 m² per blade, the total cost for the MAL across three blades is estimated at €105,000. This cost can vary significantly depending on the material chosen for the MAL, and on the specific wind turbine being considered.

The cost of magnetrons, another crucial component, varies depending on factors such as power output, cooling system, component quality, and supplier reputation. For this system, which employs 90 magnetrons per blade, and the maximum power output per source is under 1.5 kW (see Table 6.3), the unit cost ranges from €200 to €600. The total cost for the magnetrons across three blades, including necessary auxiliary equipment (e.g., power cables, conditioning systems, sensors, antennas, control systems, and mounting hardware), is estimated to be between €81,000 and €243,000. For this estimation, the costs range of the auxiliary equipment is considered half of the costs range of the total number of magnetrons. If other microwave generators were used, than the microwave sources' costs could change significantly.

Installation costs are estimated to be approximately 10% of the total investment costs, reflecting the labor and resources required to integrate the system within the wind turbine structure. Considering all these components, the total CAPEX for implementing the microwave anti-icing system ranges from €204,000 to €382,000. Table 6.4 summarizes this analysis.

Table 6.4: Estimation of total investment costs for the microwave anti-icing system

	MAL			Magnetrons			Aux. Equip-ment	Instal. Costs	Total Costs
	Price per m ²	Area per blade	Total Cost	Price per unit	Units	Total Cost	Total Cost	% of Total	
Unit	€/m ²	m ²	k€	€/un.	un.	k€	k€	%	k€
Min.	952	36.6	105	200	90	54	27	10	204
Max.	952	36.6	105	600	90	162	81	10	382

This analysis only serves as a first estimation of the system's initial costs, in a very streamlined approach, and financial decisions regarding the application of this technology would require a more in-depth analysis, which is beyond the scope of this dissertation. Further analysis could refine these estimates by considering alternative designs or integrating additional economic factors.

6.5 Comparison with Current Anti-icing Systems

This section compares the microwave anti-icing system with the two most commonly used anti-icing technologies in the wind energy industry: heating resistance systems and hot air injection systems. The comparison focuses on energy consumption, heating times, heat distribution, investment costs, reliability, and system weight.

6.5.1 Energy Consumption

The power required to heat the blade's surface is primarily determined by external conditions, blade geometry, and dimensions, rather than the specific heating method employed. Consequently, the differences in power consumption between the anti-icing systems arise from the efficiency with which each method converts electrical energy into useful heat. Heating resistance systems are highly efficient, with conversion rates close to 100%. In this study, the efficiency of which the system converted microwave energy into heat was also very close to 100%. However, it is necessary to consider the efficiency of a magnetron of converting electrical power into microwave power, which is normally between 80% and 90%, even though the losses associated with the magnetron operation will mainly be heat losses. In contrast, the hot air injection system, with an efficiency of approximately 30%, is less efficient overall.

6.5.2 Heating Times

Heating time is a critical factor in determining the overall energy consumption of the system, since less time to heat the blade to the required temperature results in less energy consumption. The microwave system is expected to have shorter heating times compared to the hot air injection system, which requires heating a large mass of air before it reaches the blade material. The heating resistance system, which is also integrated into the blade laminate, has comparable heating times. Both systems benefit from similar placements within the blade structure, allowing for efficient heat transfer and short transition times required to convert electrical energy into heat.

6.5.3 Heat Distribution

Uniform heat distribution is essential for the effectiveness of anti-icing systems. The microwave system may experience non-uniform heating due to variations in the electric field within the blade, as observed in this chapter, potentially resulting in hot and cold spots. This could result in additional power supply to ensure the cold spots reach adequate temperatures, thereby potentially wasting energy in the hot spots. Additionally, non-uniform heat distribution could limit the maximum power used due to the formation of hot spots, as discussed in Section 6.3.2. Heating resistance systems would typically provide more uniform heating along the blade, leading to more consistent anti-icing performance. However, hot spots will also be caused by the variation of the convection losses along the blade cross-section, and consequently the heating resistance system, as well as the hot air injection system, will also be affected by this non-homogeneity in temperature distribution.

Optimizing the microwave system design through the use of antennas could improve energy distribution. The hot air injection system can also have poor heat distribution, since there is no individual powering for the different sections of the blade, which could lead to lower temperatures in the sections near the tip, where more heating power is required. Unlike the hot air system, both the microwave and heating resistance systems offer the advantage of customizable power distribution along the blade, enabling more precise control and potentially better overall performance.

6.5.4 Investment Costs

Accurately comparing installation and maintenance costs is challenging, as detailed cost analysis was not the primary focus of this study. However, preliminary estimates suggest that the microwave system could be more expensive than current systems, with costs ranging from approximately €200,000 to €380,000, depending on the materials used for the MAL and the design of the microwave generation and transport systems. The manufacturing costs should also be estimated accurately for this system and compared to the other systems. While the hot air injection system is relatively simple to manufacture, the heating resistance system is complex and demands substantial auxiliary equipment.

6.5.5 Reliability

The MAL's intrinsic energy absorption properties eliminate the need for additional equipment inside the blade laminate, potentially simplifying construction and facilitating maintenance. Additionally, the system's design avoids placing power cables and electrical components near the SPL, reducing the risk of damage from lightning strikes. However, the necessity of replacing the microwave generators in regions that require continuous heating during winter times, can result in higher operational costs. This challenge could be addressed by utilizing more durable microwave sources, such as solid-state generators, which would require additional investment.

6.5.6 Weight

The weight of the microwave anti-icing system was estimated between 550 and 900 kg per blade, which is significant. Adding to this, the total weight of auxiliary equipment (power cables, power conditioning systems, sensors, antennas, control systems, and mounting hardware) has not been included in this estimate, which could increase even further the system's overall mass. This additional mass could pose risks to blade integrity, although in the considered blade the mass increase is less than 3% to 5%. Nonetheless, with careful material selection of lightweight absorbers and design optimization, the microwave system could achieve a weight comparable to or even lighter than other anti-icing systems, mitigating concerns about additional structural load.

In summary, the microwave anti-icing system offers several qualities competitive with existing technologies, particularly in heating times, potential customization of power distribution, manufacturing, and reduced safety risks. The microwave system also revealed an energy efficiency close to the heating resistance system, which is very close to 100%. However, challenges such as non-uniform heat distribution, significant weight, and high initial costs must be addressed to fully realize its potential. By comparing these systems, this study highlights the microwave system's viability and the areas where further optimization could lead to significant advancements in anti-icing technology. To fully assess the competitive potential of the studied system against current anti-icing technologies, a more comprehensive comparison is necessary, along with an in-depth examination of the alternative components and configurations for the microwave system.

Chapter 7

Conclusions

This dissertation presents an extensive preliminary study on the feasibility of using microwave energy absorption to develop a competitive anti-icing technology for wind turbine blades. Exploring the viability of new technologies, particularly in complex fields like wind energy, is inherently challenging and demands consideration of multiple factors.

While there have been some theoretical studies on microwave anti-icing systems, limited numerical simulations and experimental tests have been conducted. This dissertation extends beyond theoretical concepts by critically examining the practical implementation of such systems in wind turbine applications through numerical simulations and a thorough analysis of the results.

The working principle was well established: microwave generation inside the blade, emission toward a microwave absorbing material embedded in the blade laminate, absorption of microwaves and conversion into heat, followed by heat propagation to the surface. Additionally, various system designs were explored in the study, although a comprehensive comparison of different components and configurations for microwave generation and emission would require a dedicated investigation.

The absorption and heat conversion mechanisms were examined in detail, identifying the use of microwave absorbing materials embedded within the blade laminate as the best solution for heating the blade surface. While this study did not aim to conclude on the best absorber material, as this would require a full investigation dedicated to this topic, to study the heating system viability, the microwave absorbing layer (MAL) needed to include an excellent microwave absorber, otherwise a high heating efficiency would never be achieved. Therefore, an extensive research on potential materials and respective properties was conducted.

One of the key contributions of this work is the development of reliable numerical models for an initial feasibility analysis. Four models of a simplified microwave anti-icing system were developed in COMSOL software: two 3D models with flat plate geometry (one focusing on the MAL and the other incorporating blade materials), and two 2D models of a wind turbine blade cross-section (one with a constant convection coefficient and the other including CFD analysis). COMSOL models incorporating blade materials presented results consistent with a transient model

developed in EES software. The flat plate model with blade laminate materials enables the visualization of electromagnetic fields in 3D, although with a simplified geometry. In contrast, the CFD model simulates more realistic conditions, despite only capturing effects in 2D. Accurate simulations of this system are highly dependent on the precise characterization of material properties, particularly the permittivity and permeability of the absorber at the selected frequency.

Based on initial material selection and simulations in the developed models, Eccosorb BSR-1, available from the supplier Laird, was identified as the most suitable absorber, along with the definition of its optimal thickness (3 mm) and optimal placement inside the blade. These results showed that the blade surface could be heated above 0°C, with heating times dependent on the power supply and atmospheric conditions. The optimized MAL achieved the most uniform surface temperature distribution of the analysed materials and parameters, although low temperatures were observed near the leading edge and shear webs, for the specific airfoil under study. An absorption efficiency of microwave power of 98.5% was achieved, for a microwave frequency of 2.45 GHz.

Among the microwave system designs considered in this thesis, one involving multiple magnetrons attached to the shear web inside the blade was analysed in detail. This simple design did not include advanced emission systems like horn antennas, which could enhance heat distribution across the blade cross-section. For this specific design, an optimal number of 90 magnetrons per blade was obtained for a 70 m blade, with the microwave heating system covering 2/3 of its full length. This setup corresponds to an approximate spacing of 0.5 m between magnetrons.

The power and temperature constraints of 93.3 kW and 55 °C, respectively, can be respected until a certain level of severe atmospheric conditions, similarly to the other current anti-icing technologies. Under extreme conditions, anti-icing is not possible and the turbine requires to pause operation for de-icing. For harsh conditions where anti-icing is possible, the maximum power required is less than 1.5 kW per magnetron near the blade tip, for the considered blade.

For the analysed design, for the considered wind turbine, the additional mass and investment costs were estimated, resulting in an increase of less than 3% to 5% in the blade's mass, and total investment costs ranging from 200 to 380 thousand euros, depending on various factors such as design implementation, auxiliary equipment, raw material prices, and manufacturing processes.

Currently, heating resistance systems are favored due to their high heating efficiency, control flexibility, and rapid heating capabilities. To assess whether the microwave-based system could compete with heating resistance systems, a more complete and comprehensive comparison of the detailed costs, manufacturing processes, additional mass, and consumed energy is necessary. Ease of maintenance and durability also need to be taken into account.

7.1 Main Conclusions of the Dissertation

This section highlights the key conclusions drawn from this dissertation.

- Several configurations can be designed for the generation, transport, and emission of microwaves within the blade, although the absorption and heat conversion should be conducted by a microwave absorbing layer (MAL) embedded in the blade laminate.

- The MAL should be positioned near the surface but beneath the lightning protection system's metallic layer, ideally separated by a layer of glass fibre or similar material. It should be placed only in the region between the leading edge and the shear web.
- The MAL material must exhibit excellent dielectric or magnetic loss properties with low penetration depths to enable optimal absorption at reduced thicknesses. Additionally, it should have low electrical conductivity to mitigate lightning risks, a considerable thermal conductivity for fast heating, and low density to minimize the overall mass.
- Absorption efficiencies close to 100% are achievable with appropriate MAL materials. While overall power efficiency might be slightly lower than that of heating resistance systems, due to additional losses in the microwave source that could result in non-useful heat, it remains competitive.
- Non-uniform electric field distribution within the blade can cause hot and cold spots on the blade surface, potentially reducing ice prevention effectiveness. Optimized microwave emission systems can mitigate this issue.
- The maximum spacing between interior microwave sources is estimated to be around 0.5 meters. However, a 3D model of a full wind turbine is necessary to accurately assess the reach of a single source, which would also depend on the emission system used.
- Using multiple microwave sources inside the blade ensures flexibility in powering different blade regions individually. Each source would require less than 1.5 kW, decreasing power demand towards the blade root. If a greater spacing between sources can be implemented without compromising heat distribution, fewer sources with more power could be used.
- Magnetrons may not last the entire lifespan of the wind turbine, particularly in extreme cold climates, necessitating replacement. To avoid this, the use of more durable solid-state microwave generators could be explored.
- As with current anti-icing systems, it is crucial to establish the critical atmospheric conditions under which the microwave anti-icing system can operate effectively. Under conditions where power supply is enough, the blade surface can be heated in few minutes, respecting both the maximum power supply available and maximum temperature of the blade materials. Low heating times are essential for minimizing energy consumption during operation.
- Initial estimates suggest that the microwave system may involve high investment costs (200-380 k€). The added mass is also significant, although it constitutes less than 3-5% of the total blade weight. The design keeps critical components inside the blade, enhancing reliability and reducing the risk of environmental damage, such as from lightning strikes.
- Compared to current anti-icing systems, the microwave system offers several interesting qualities, including the absence of power and electrical components within the laminate, potentially shorter heating times, theoretical ease of manufacturing and integration, and high power efficiency with flexible heating tailored to section-specific requirements. Challenges related to cost, maintenance, heat distribution, and durability must be further addressed for it to fully compete with established technologies.

7.2 Study Limitations and Future Works

The study provides a comprehensive initial exploration of a microwave anti-icing system for wind turbine blades but is based on simplified models and assumptions that may not fully reflect real-world complexities. Several limitations and areas for future research have been identified.

One limitation is the variability in material properties with changes in temperature and frequency. The study focused on a single frequency of 2.45 GHz and did not fully account for how dielectric and magnetic losses in microwave-absorbing materials may vary under different conditions. Future research on absorber materials should also include experimental testing, durability studies, lightning risk assessments, and compatibility evaluations with other blade materials.

The study also simplified the geometric variability along the blade length, analyzing a specific section of the blade and assuming consistent conditions along its length. Wind turbine blades exhibit varying cross-sections, different shear web locations, and sometimes multiple shear webs, all of which could influence the anti-icing system. Future work should include 3D modeling of the blade, using these models to accurately determine the maximum spacing between sources.

The effect of the angle of attack, which could influence the temperature distribution, was not investigated. This, along with the potential impacts of other blade material compositions, suggests that a broader analysis is needed to study a wider range of operational conditions.

Optimal coverage of the blade surface area by the microwave heating system was not deeply explored, and further research could maximize efficiency while minimizing weight and cost. Additionally, integrating the MAL with the lightning protection system requires further investigation.

In terms of system design, alternative emission systems such as slotted waveguides or horn antennas should be explored to optimize microwave transmission and improve heat distribution uniformity. Placement of microwave sources, whether at the blade root or along its length, and the use of solid-state microwave generators should also be explored to enhance durability and reduce maintenance needs. Alternatives to avoid maintenance close to the blade tip should also be studied.

The study's power requirements were calculated without considering factors like the droplet diameter and liquid water content of air, which could impact ice accretion and the necessary anti-icing power. Future research should integrate these factors into a more accurate power requirement model, and also define the critical atmospheric conditions for microwave anti-icing system operation, establishing the maximum power requirements. Integration with ice prediction and control systems would also be crucial for optimizing system activation and performance.

Accurate calculations of the system's mass, including auxiliary equipment and material weights provided by suppliers, are necessary for a realistic assessment. This should be complemented by a calculation of the percentage increase in centrifugal forces in the blade. A thorough cost analysis is also required, including complete investment costs and operational expenses (OPEX). The study should also identify challenges in manufacturing and integrating this system within the blade, and explore the feasibility of retrofitting existing wind turbines with this technology.

Further advancements on the investigation of this technology would require experimental validation and field testing.

Appendix A

Mathematical Formulation

This appendix presents the mathematical formulations essential for comprehending the fundamental principles addressed in this dissertation. Although the approach of this mathematical model is a simplified examination of a highly intricate aspect of physics, it includes critical deduction processes designed to elucidate the behavior of microwave heating and its dependent factors. These deduction processes aim to make a more comprehensive analysis to the equations employed by the multiphysics software utilized in subsequent problem-solving. While it may appear that the software autonomously manages the mathematical formulation, it is imperative to understand the underlying mathematical model, as some equations used by the software may represent variations or simplifications of those found in the literature. A detailed examination of electromagnetic field behavior and the physical expression of electromagnetic heating is crucial for a better understanding of how to model accurate and realistic microwave systems.

This appendix also details the mechanisms of microwave absorption and characterizes it using specific parameters, essential for evaluating microwave heating performance under varying conditions and across different materials. By focusing on these aspects, this chapter underscores the significance of a robust mathematical foundation for the accurate and effective application of microwave heating technologies in diverse scientific and engineering contexts.

A.1 Electromagnetic Fields

In 1864, Maxwell introduced his pivotal work, *A Dynamical Theory of the Electromagnetic Field*. This groundbreaking theory integrated over a century of experimental research into a comprehensive set of equations, now famously known as Maxwell's equations. These equations were experimentally validated by Hertz in 1887 through a series of impressive demonstrations. Presently, Maxwell's equations are acknowledged as the cornerstone of our comprehension of all electromagnetic phenomena, including electromagnetic microwaves [85].

These equations, which consist of both differential and integral forms, describe the interaction between key electromagnetic properties and are typically solved using the finite element method (FEM) [86].

The differential form of Maxwell's equations is as follows [85]:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (\text{A.1})$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (\text{A.2})$$

$$\nabla \cdot \mathbf{D} = \rho_v \quad (\text{A.3})$$

$$\nabla \cdot \mathbf{B} = 0, \quad (\text{A.4})$$

where $\mathbf{E}$ represents the electrical field, $\mathbf{H}$ the magnetic field, $\mathbf{B}$ the magnetic flux density, $\mathbf{J}$ the electric current density, $\mathbf{D}$ the electric flux density and ρ_v represents the electric volume charge density.

The relationships between the electric flux density, ($\mathbf{D}$), and the magnetic flux density, ($\mathbf{B}$), are given by [85]:

$$\mathbf{D} = \epsilon \mathbf{E} \quad (\text{A.5})$$

$$\mathbf{B} = \mu \mathbf{H}, \quad (\text{A.6})$$

where ϵ is the permittivity and μ the permeability. Additionally, the electric current density $\mathbf{J}$ is expressed as:

$$\mathbf{J} = \sigma \mathbf{E}, \quad (\text{A.7})$$

where σ is the electrical conductivity.

For a source-free homogeneous medium, the instantaneous Maxwell's equations can be represented as [87] [85]:

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad (\text{A.8})$$

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \epsilon \frac{\partial \mathbf{E}}{\partial t} \quad (\text{A.9})$$

$$\nabla \cdot \mathbf{E} = 0 \quad (\text{A.10})$$

$$\nabla \cdot \mathbf{H} = 0 \quad (\text{A.11})$$

Using phasor notation, these equations can be transformed into the frequency domain as:

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}, \quad (\text{A.12})$$

$$\nabla \times \mathbf{H} = \sigma\mathbf{E} + j\omega\epsilon\mathbf{E}, \quad (\text{A.13})$$

$$\nabla \cdot \mathbf{E} = 0, \quad (\text{A.14})$$

$$\nabla \cdot \mathbf{H} = 0, \quad (\text{A.15})$$

The transformation and mathematical manipulation of these equations yield the instantaneous wave equations (Helmholtz equations) in both time and frequency domains [87] [85]:

Time domain:

$$\nabla^2 \mathbf{E} = \mu\sigma \frac{\partial \mathbf{E}}{\partial t} + \mu\epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} \quad (\text{A.16})$$

$$\nabla^2 \mathbf{H} = \mu\sigma \frac{\partial \mathbf{H}}{\partial t} + \mu\epsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} \quad (\text{A.17})$$

Frequency-domain:

$$\nabla^2 \mathbf{E} = j\omega\mu(\sigma + j\omega\epsilon)\mathbf{E} \quad (\text{A.18})$$

$$\nabla^2 \mathbf{H} = j\omega\mu(\sigma + j\omega\epsilon)\mathbf{H} \quad (\text{A.19})$$

We can simplify the Maxwell's equations to a fundamental curl-curl equation that governs the propagation of electromagnetic waves.

Using the Helmholtz equation in the frequency domain A.18, equations 2.3 and 2.4, and using the following relationships:

$$\epsilon_0\mu_0 = \frac{1}{c_e^2} \quad (\text{A.20})$$

$$k_0 = \frac{\omega}{c_e}, \quad (\text{A.21})$$

where k_0 and c_e are the free space wave number and the velocity of electromagnetic waves, the following deduction process was obtained:

$$-\nabla \times (\nabla \times \mathbf{E}) = j\omega\mu_0\mu_r(\sigma + j\omega\epsilon_r\epsilon_0)\mathbf{E} \quad (\text{A.22})$$

$$-\nabla \times \frac{1}{\mu_r}(\nabla \times \mathbf{E}) = j\omega\mu_0\sigma\mathbf{E} - \frac{\omega^2\epsilon_r\mathbf{E}}{c^2} \quad (\text{A.23})$$

$$-\nabla \times \frac{1}{\mu_r}(\nabla \times \mathbf{E}) = -k_0^2 \left(\epsilon_r - j\frac{\sigma}{\omega\epsilon_0} \right) \mathbf{E} \quad (\text{A.24})$$

$$-\nabla \times \frac{1}{\mu_r}(\nabla \times \mathbf{E}) + k_0^2 \left(\epsilon_r - j\frac{\sigma}{\omega\epsilon_0} \right) \mathbf{E} = 0 \quad (\text{A.25})$$

$$\nabla \times \frac{1}{\mu_r}(\nabla \times \mathbf{E}) - k_0^2 \left(\epsilon_r - j\frac{\sigma}{\omega\epsilon_0} \right) \mathbf{E} = 0 \quad (\text{A.26})$$

In summary, Maxwell's equations, combined with the constitutive relations of media, allow for the calculation of the electric field using equation A.26 [57, 74, 86].

Another important concept to consider on microwave propagation is the definition of a plane wave. These waves are simplified approximations of electromagnetic waves and may be characterized by the following properties: (1) $\mathbf{E}$ and $\mathbf{H}$ lie in a plane perpendicular to the direction of propagation, and (2) $\mathbf{E}$ and $\mathbf{H}$ are perpendicular to each other. When these fields are uniform in any plane perpendicular to the direction of propagation, the wave is denominated a uniform plane wave [85, 87].

A transverse electromagnetic (TEM) wave can be considered as any wave that has no electric or magnetic field components in the direction of propagation and is often used in guided structures, such as waveguides.

A.2 Electromagnetic Heating

Poynting's theorem represents the fundamental principle of energy conservation for electromagnetic fields. By employing Poynting's theorem, it is possible to ascertain all sources of energy associated with electromagnetic fields within a specified volume. The corresponding Poynting vector, $\mathbf{P}_p$, defines the vector power density (direction and density of power flow at a point) [46]:

$$\mathbf{P}_p = \mathbf{E} \times \mathbf{H} \quad (\text{A.27})$$

The product of $\mathbf{E}$ and $\mathbf{H}$ gives units of W/m^2 . For uniform plane waves, the direction of $\mathbf{E} \times \mathbf{H}$ gives the direction of wave propagation (the direction of power flow). Thus, we seek a relationship defining the cross product of $\mathbf{E}$ and $\mathbf{H}$ [87].

For a time-harmonic field, the time average Poynting vector is found by integrating the instantaneous Poynting vector over one period and dividing by the period:

$$\mathbf{P}_{ave} = \frac{1}{T} \int_T (\mathbf{E} \times \mathbf{H}) dt \quad (\text{A.28})$$

In the frequency-domain, $\mathbf{E}$ and $\mathbf{H}$ are used as phasors and, through trigonometric operations and integrating over a given volume V (enclosed by a surface S), we can reduce the time-average Poynting vector to [46]:

$$\mathbf{P}_{\text{ave}} = -\frac{1}{2} \int_{s'} \text{Real}(\mathbf{E} \times \mathbf{H}^*) \cdot d\mathbf{s}', \quad (\text{A.29})$$

where $\mathbf{E} \times \mathbf{H}^*$ is defined as the phasor Poynting vector and is normally represented by S .

To derive Poynting's theorem, we start with the frequency-domain Maxwell curl equations, A.12 and A.13: Starting by equation A.13, the deduction process is as follows [46]:

$$\nabla \times \mathbf{H} = j\omega\epsilon\mathbf{E} + \mathbf{J}, \quad (\text{A.30})$$

$$\nabla \times \mathbf{H} = j\omega\epsilon_p\mathbf{E} + \sigma\mathbf{E}, \quad (\text{A.31})$$

$$\nabla \times \mathbf{H} = (\omega\epsilon_p'' + j\omega\epsilon_p')\mathbf{E} + \sigma\mathbf{E}, \quad (\text{A.32})$$

$$\nabla \times \mathbf{H} = \omega\epsilon_0 \left(\epsilon_p'' + \frac{\sigma}{\omega\epsilon_0} \right) \mathbf{E} + j\omega\epsilon_0\epsilon_p'\mathbf{E}, \quad (\text{A.33})$$

$$\nabla \times \mathbf{H} = \omega\epsilon_0\epsilon_r''\mathbf{E} + j\omega\epsilon_0\epsilon_r'\mathbf{E}. \quad (\text{A.34})$$

And doing the same for A.12, we obtain:

$$\nabla \times \mathbf{E} = -\omega\mu_0\mu_r''\mathbf{H} - j\omega\mu_0\mu_r'\mathbf{H}. \quad (\text{A.35})$$

Knowing that:

$$\int_{s'} (\mathbf{E} \times \mathbf{H}^*) \cdot d\mathbf{s}' = \int_V \nabla \cdot (\mathbf{E} \times \mathbf{H}^*) dV, \quad (\text{A.36})$$

and that:

$$\nabla \cdot (\mathbf{E} \times \mathbf{H}^*) = (\nabla \times \mathbf{E}) \cdot \mathbf{H}^* - (\nabla \times \mathbf{H}^*) \cdot \mathbf{E}, \quad (\text{A.37})$$

we obtain:

$$\int_{s'} (\mathbf{E} \times \mathbf{H}^*) \cdot d\mathbf{s}' = \int_V [-\omega\mu_0\mu_r''\mathbf{H} \cdot \mathbf{H}^* - \omega\epsilon_0\epsilon_r''\mathbf{E} \cdot \mathbf{E}^*] dV - j\omega \int_V [(\mu_0\mu_r'\mathbf{H} \cdot \mathbf{H}^* - \epsilon_0\epsilon_r'\mathbf{E} \cdot \mathbf{E}^*)] dV. \quad (\text{A.38})$$

Thus, using equation A.29 and substituting with the above equation (A.38), it can be shown that [46]:

$$\mathbf{P}_{\text{ave}} = \frac{1}{2} \omega\epsilon_0\epsilon_r'' \int_V (\mathbf{E} \cdot \mathbf{E}^*) dV + \frac{1}{2} \omega\mu_0\mu_r'' \int_V (\mathbf{H} \cdot \mathbf{H}^*) dV, \quad (\text{A.39})$$

$$\mathbf{P}_{\text{ave}} = \frac{1}{2} \omega\epsilon_0\epsilon_r'' E^2 V + \frac{1}{2} \omega\mu_0\mu_r'' H^2 V. \quad (\text{A.40})$$

The electromagnetic power dissipated per unit volume, P , can now be finally stated as:

$$P = \frac{1}{2} \omega \epsilon_0 \epsilon_r'' E^2 + \frac{1}{2} \omega \mu_0 \mu_r'' H^2. \quad (\text{A.41})$$

As delineated in the equation above, microwave heating is dependent upon several factors, including the microwave frequency, the dielectric and magnetic loss factors of the material, as well as the microwave electric and magnetic field strengths. It is also very important to highlight that ϵ_r'' used on the above equation includes both terms of polarization loss and conduction loss, as explicit on the simplification from equation A.33 to equation A.34 [46].

The demonstration above elucidates the influence of electromagnetic fields on microwave heating. However, it is imperative to also consider the heat energy transfer and distribution within the heated materials. Microwaves primarily function as a heat source for the absorber, with the subsequent heat propagation governed by the principles of heat transfer. The general equation for heat diffusion, commonly referred to as the conservation of energy equation, in Cartesian coordinates can be expressed by [88]:

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t}, \quad (\text{A.42})$$

where k , ρ , and c_p represent the material thermal conductivity, density, and specific heat capacity, respectively. T defines the temperature and $\dot{q}$ the internal heat generation.

In scenarios where heat generation arises from microwave heating, the heat transfer equation is modified as follows [89]:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = P, \quad (\text{A.43})$$

This modified equation accounts for the additional heat generation due to the dissipation of electromagnetic energy within the material.

As demonstrated in this section, microwave heating is intrinsically linked to the propagation and dissipation of microwaves within materials, which are typically characterized mathematically by Maxwell's equations along with their corresponding boundary conditions. The distributions of the microwave field within an absorber are determined by these equations, and any variations will significantly impact heating efficiency. Consequently, to enhance microwave heating efficiency, the primary consideration must be to maximize the absorption of microwave energy.

A.3 Microwave Absorption

Microwave absorption has been addressed in section 2.5.2, where the equations for permittivity and permeability are presented. Understanding these properties is essential for comprehending the mechanisms of microwave absorption and defining the characteristics of effective microwave absorbing materials, which is why their formulation is shown previously to this chapter.

In addition to the mentioned factors that influence microwave heating, such as microwave frequency, absorption properties (permittivity and permeability), and electromagnetic field distribution, material thickness is also a critical consideration when characterizing absorption capacity. Microwave heating efficiency is influenced not only by heat generation within the absorber but also by the heat transfer inside it during the heating process, as characterized by equation A.43. Consequently, the dimensions of the absorber also affect the homogeneity of temperature distribution within it. Moreover, variations in material dimensions alter the proportions of reflected, transmitted, and absorbed energy, making the parameters detailed in the following sections essential for characterizing the impact of thickness on microwave absorption [46, 57].

A.3.1 Absorption Parameters

As previously discussed, to enhance microwave heating efficiency, it is crucial to minimize reflection and transmission. Various parameters, which can be measured or calculated for a material with specific dimensions, help quantify absorption efficiency by defining the reflection, transmission, and absorption components. Given the necessity to characterize microwave absorption under specific conditions, evaluating the parameters presented in this section is fundamental for designing systems that require optimized microwave heating efficiency. This comprehensive evaluation not only aids in the precise tailoring of material properties but also helps to enhance the overall performance and efficiency of microwave-based applications.

Attenuation Factor

Firstly, it is of great importance to define, for a given material, how much of the penetrating waves will be attenuated inside the material. This can be achieved by calculating the attenuation factor, which gives the dissipation, or attenuation, of microwaves per length unit.

The attenuation factor (α) (Np/m) is, therefore, a parameter which characterizes the intrinsic capacity of the microwave absorbing material to dissipate the incident electromagnetic microwaves, thereby characterizing the microwave absorption performance. For magnetic dielectrics, where magnetic susceptibility is considerable, it is imperative that the equation incorporates both dielectric and magnetic losses [86].

To comprehend the physical meaning of the attenuation factor, we can once again refer to Maxwell's equations. In a homogeneous medium and without convection or external currents, the differential Maxwell's equations in the frequency domain are expressed by equations A.12, A.13, A.14 and A.15 [90].

Considering vector multiplication for Maxwell's equations, we obtain the Helmholtz equations defined by equations A.18 and A.19, that can be simplified to [90]:

$$\nabla^2 \mathbf{E} - \gamma^2 \mathbf{E} = 0, \quad (\text{A.44})$$

$$\nabla^2 \mathbf{H} - \gamma^2 \mathbf{H} = 0. \quad (\text{A.45})$$

Here, γ represents the propagation constant, a complex number that can be expressed as:

$$\gamma = \alpha + j\beta, \quad (\text{A.46})$$

where α is the field attenuation factor (Np/m), and β is the phase constant (rad/m). Using the definition of the propagation constant and separating the real part, we obtain α [90]:

$$\alpha = \frac{\sqrt{2\pi}}{\lambda_0} \left\{ \epsilon_r'' \mu_r'' - \epsilon_r' \mu_r' + [(\epsilon_r' \mu_r'')^2 + (\epsilon_r'' \mu_r')^2 + (\epsilon_r' \mu_r'')^2 + (\mu_r' \epsilon_r'')^2]^{1/2} \right\}^{1/2}, \quad (\text{A.47})$$

where λ_0 is the wavelength of the microwave in free-space, defined as:

$$\lambda_0 = \frac{c_e}{f}, \quad (\text{A.48})$$

where f is the microwave frequency.

Essentially, an increase in the attenuation factor (α) indicates a higher degree of microwave energy dissipation, or absorption, within the microwave absorbing material, which is critical for enhancing the material's efficiency in converting microwave energy into thermal energy. However, excessively high values of this factor can mean that all incident power is being absorbed near the surface, resulting in inhomogeneous temperature distribution.

Penetration Depth

A parameter that is closely linked to the attenuation factor is the penetration depth, D_p . It characterizes the depth to which electromagnetic microwave radiations penetrate a material, and is a critical factor influencing the absorbed microwave energy by the specimen. This parameter defines the distance at which the traveling wave power density decays to $1/e$ (approximately 0.368) of its original amplitude [46, 57, 86, 90].

As mentioned, as the wave propagates through the medium, it experiences attenuation, resulting in the dissipation of power. Power penetration depth is defined as follows [90]:

$$D_p = \frac{1}{2\alpha}, \quad (\text{A.49})$$

which can be further developed into the expression [90]:

$$D_p = \frac{\lambda_0}{2\sqrt{2\pi}} \left\{ \epsilon_r'' \mu_r'' - \epsilon_r' \mu_r' + [(\epsilon_r' \mu_r'')^2 + (\epsilon_r'' \mu_r')^2 + (\epsilon_r' \mu_r'')^2 + (\mu_r' \epsilon_r'')^2]^{1/2} \right\}^{-1/2} \quad (\text{A.50})$$

The above equation is, therefore, the formula for determining the penetration depth of magnetic dielectrics. This quantity is inversely proportional to attenuation factor, so a higher attenuation means a lower penetration depth, and vice-versa. Neglecting magnetic effects and assuming $\mu_r = 0$, it simplifies to:

$$D_p = \frac{\lambda_0}{2\pi(2\varepsilon_r')^{1/2}} \left\{ \left[1 + \left(\frac{\varepsilon_r''}{\varepsilon_r'} \right)^2 \right]^{1/2} - 1 \right\}^{-1/2} \quad (\text{A.51})$$

Or equivalently:

$$D_p = \frac{c_e}{2\pi f \sqrt{2\varepsilon_r'}} \left(\sqrt{(1 + \tan^2(\delta_\varepsilon))} - 1 \right)^{-\frac{1}{2}} \quad (\text{A.52})$$

Another important and commonly used parameter for characterizing microwave absorption is the field penetration depth, also known as the skin depth or field attenuation length (D_f). It can be mathematically expressed as twice the penetration depth, or [50]:

$$D_f = \frac{1}{\alpha}. \quad (\text{A.53})$$

This parameter also measures the depth of microwave penetration in a material and is defined as the distance from the surface to the point at which the magnitude of the field strength drops to e^{-1} (approximately 0.368) of its value at the surface [50].

Greater penetration depth achievable at standard microwave frequencies is also one of the reasons why microwave heating presents substantial advantages over infrared heating. In conventional furnaces, infrared radiation heats only a thin surface layer of materials owing to its limited penetration depth, necessitating heat transfer through conduction for deeper heating, which is a time-intensive process. In contrast, microwaves can penetrate deeper into materials, facilitating more uniform and rapid volumetric heating. This characteristic is crucial for enhancing energy efficiency and optimizing material dimensions for heating applications [46].

The penetration depth is also critical in determining the optimal dimensions of materials for microwave absorption. Materials with dimensions significantly larger than their penetration depth tend to exhibit non-uniform heating, resulting in inhomogeneous temperature distributions. Conversely, materials with a thickness much smaller than the penetration depth permit most microwaves to transmit without substantial attenuation, thereby diminishing energy absorption. Hence, the thickness of materials should ideally be comparable to their penetration depth to ensure efficient microwave absorption and uniform heating. Understanding and optimizing penetration depth is essential for efficient and uniform microwave heating processes. Furthermore, impedance matching and reflection loss must be considered for accurate dimension optimization, as these parameters vary with thickness and influence the amount of energy reflected by the material [46, 50].

Impedance Matching

As discussed in Section 2.5.2, the quantity of incident electromagnetic microwaves entering the absorbing material is influenced by the degree of impedance matching (Z). Achieving an optimal impedance match, when the value of Z approaches 1, ensures the efficient entry of electromagnetic microwaves into the absorbing material, thereby enhancing the absorption of electromagnetic

waves within the material and minimizing the reflection of incident radiation. The impedance matching can be determined using the following expression [45, 86]:

$$Z = \left| \frac{Z_i}{Z_0} \right|, \quad (\text{A.54})$$

where Z_0 defines the impedance of free space and is expressed by [45]:

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}, \quad (\text{A.55})$$

and Z_i represents the impedance of the absorber, and can be calculated using the following equation [45]:

$$Z_i = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \left(\frac{2\pi f d}{c_e} \sqrt{\epsilon_r \mu_r} \right) \right], \quad (\text{A.56})$$

where d corresponds to the absorber thickness. It is important to emphasize that ϵ_r and μ_r are complex numbers, as previously defined, which makes Z the magnitude of a complex number.

Reflection Loss

To further characterize microwave absorption, it is important to quantify the portion of the incident microwaves that is being reflected. For this purpose, it is widely used a parameter denominated reflection loss (RL), expressed in dB, which can be evaluated using the following expression, for perpendicular incidence [86]:

$$\text{RL} = 20 \log \left| \frac{Z - 1}{Z + 1} \right| \quad (\text{A.57})$$

Substituting the previously defined degree of impedance matching (Z), it is shown that [45, 57]:

$$\text{RL} = 20 \log \left| \frac{\sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \left(\frac{2\pi f d}{c} \sqrt{\epsilon_r \mu_r} \right) \right] - 1}{\sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \left(\frac{2\pi f d}{c} \sqrt{\epsilon_r \mu_r} \right) \right] + 1} \right| \quad (\text{A.58})$$

According to transmission line theory, the quantity $\frac{Z-1}{Z+1}$ in equation A.57 represents the reflection coefficient, denoted as R . The power reflection coefficient is defined as R^2 . As a consequence of this definition, lower (more negative) RL values correspond to reduced reflection. For example, an RL of -10 dB indicates a power reflection coefficient of 10%, meaning that RL values lower than -10 dB signify that less than 10% of microwave incident energy is being reflected from the surface of the material. When RL reaches values of -20dB or lower it means that only 1% or less of the incident microwave energy is being reflected [45, 46, 57].

As seen from equation above (A.58), various factors affect a material's microwave reflection loss such as permeability, permittivity, thickness, and frequency. Equation A.57 also shows that

a perfect impedance matching of 1 would result in $RL = -\infty$, meaning that none of the incident microwave power would be reflected [45].

The conjugation of the parameters mentioned in this section will determine the absorption capabilities of a material for specific thicknesses and frequencies. It is fundamental to reduce the reflected energy, while at the same time reducing the transmitted microwaves. Assessing this parameters can help optimize material thickness and system frequency, to achieve enhanced microwave heating. However, it is essential to consider that the material properties, particularly permittivity and permeability, significantly influence these parameters. These properties vary with frequency and temperature, resulting in a complex analysis when evaluating the optimal system parameters.

Appendix B

Boundary Conditions of Microwave Heating Models in COMSOL

This appendix focus exclusively on the boundary conditions used in the three different studies employed for benchmarking.

B.1 Port

Ports are used to define where electromagnetic energy enters (or exits) the model. There are different wave type ports available, but in this case we are only interested in rectangular ports as the waves enter the model through a rectangular waveguide. For these cases, the waveguide is set to operate at transverse electric 10 (TE₁₀) mode, which has no electric field component in the direction of propagation, and is excited with different input powers [91].

The propagation constant of electromagnetic waves, γ , is expressed by [57, 75]:

$$\gamma = \frac{2\pi}{c_e} \sqrt{f^2 - f_c^2}, \quad (\text{B.1})$$

where f_c is the cutoff frequency, below which waves can not propagate efficiently, defined by [74]:

$$f_c = \frac{c_e}{2} \sqrt{\frac{m^2}{a^2} + \frac{n^2}{b^2}} \quad (\text{B.2})$$

where m and n are integers representing the number of half-wavelength variations of the field in the broader dimension (width, a) and the narrower dimension (height, b) of the waveguide, respectively. They define the TE_{mn} mode, and in this case $m = 1$ and $n = 0$, which simplifies equation B.2 to:

$$f_c = \frac{c_e}{2a} \quad (\text{B.3})$$

B.2 Impedance boundary condition

The Impedance Boundary Condition (IBC) is an approximation for modeling electromagnetic fields at boundaries where the field penetrates only a short distance outside the boundary. IBC approximates the electromagnetic field penetration to avoid the need to include additional domains in the model, thereby simplifying the computational problem [92].

The IBC is a valid approximation when the skin depth is small compared to the size of the conductor. Therefore, this condition is particularly applicable on exterior boundaries representing the surface of a domain with high losses. For metals, the skin depth is typically on the order of less than 10 μm , which makes this boundary condition perfectly suitable [92].

For a good conductor, the skin depth, D_f , can be simplified to [57, 74, 92]:

$$D_f = \sqrt{\frac{2}{\omega\mu\sigma}}. \quad (\text{B.4})$$

The mathematical formulation of the IBC is expressed as [92]:

$$\sqrt{\frac{\mu_r\mu_0}{\epsilon_r\epsilon_0} - \frac{j\sigma}{\omega}} \mathbf{n} \times \mathbf{H} + \mathbf{E} - (\mathbf{n} \cdot \mathbf{E})\mathbf{n} = (\mathbf{n} \cdot \mathbf{E}_s)\mathbf{n} - \mathbf{E}_s. \quad (\text{B.5})$$

The material properties that appear in the equation above belong to the conductive material. The IBC effectively accounts for the heat lost to the walls of the cavity due to the skin effect [75].

B.3 Thermal Insulation Boundary Condition

Thermal insulation boundary condition is applied to prevent any heat flux across the boundary. It avoids the need to include domains of exterior insulation materials, and is represented by [57, 74]:

$$-\mathbf{n} \cdot \mathbf{q} = -\mathbf{n} \cdot (-k\nabla T) = 0 \quad (\text{B.6})$$

B.4 Heat Flux Boundary Condition

Applying a heat flux to a boundary is essential in various scenarios. Whether a surface is subjected to forced or natural convection, this approach eliminates the need to model fluid flow outside (or inside) that boundary, which is more challenging and significantly increases computational effort. For these initial simulations, only convective heat flux will be considered, which can be expressed by [75, 88]:

$$-\mathbf{n} \cdot (-k\nabla T) = h \cdot (T_\infty - T), \quad (\text{B.7})$$

where h represents the convection heat transfer coefficient, which can be manually defined in COMSOL or calculated by the software for specific geometries, fluid properties and fluid velocities.

Appendix C

Materials Properties Used by Each Study - Benchmarking

Tables C.1, C.2, and C.3 detail the material properties used in Studies 1, 2, and 3, respectively.

Table C.1: Properties of materials used in Study 1. Temperatures are in Kelvin [57]

Material Properties	SiC
Relative permeability	1
Thermal conductivity (W/(m · K))	No data
Density (kg/m ³)	No data
Specific Heat (J/(kg · K))	No data
Relative permittivity (real part)	$(0.00000188 T^2) - (0.00167 T) + 6.4$
Relative permittivity (imaginary part)	$0.992 - (0.000343 T) + (0.00000772 T^2) - (0.00000000715 T^3) + (0.00000000000236 T^4)$
Electrical conductivity (S/m)	No data

Table C.2: Properties of materials used in Study 2. AL₂O₃ is the base material and temperatures are in Kelvin [74]

Material Properties	SiC	Al ₂ O ₃	Copper	Air
Relative permeability	1	1	1	1
Thermal conductivity (W/(m · K))	$8E - 5 T^2 - 0.325 T + 326.69$	0.32	400	0
Density (kg/m ³)	3210	2770	8960	–
Specific Heat (J/(kg · K))	$4E - 7 T^3 - 0.0017 T^2 + 2.3729 T + 115.43$	885	385	–
Relative permittivity	9.6	4.3	1	1
Electrical conductivity (S/m)	0.02	1E – 14	5.998E7	0

Table C.3: Properties of the materials used in Study 3. Al_2O_3 is the base material and temperatures are in Kelvin [75]

Material Properties	SiC	Al_2O_3	Copper	Air
Relative permeability	1	1	1	1
Thermal conductivity (W/(m · K))	$8E - 5T^2 - 0.325T + 326.69$	0.32	400	0
Density (kg/m ³)	3100	2770	8700	–
Specific Heat (J/(kg · K))	$4E - 7T^3 - 0.0017T^2 + 2.3729T + 115.43$	885	385	–
Relative permittivity (real part)	$-0.0002T^2 + 0.4503T + 124.26$	4.3	1	1
Loss tangent	$5E - 10T^3 - 9E - 07T^2 + 0.0006T + 0.2801$	–	–	–
Electrical conductivity (S/m)	–	$1E - 14$	5.998E7	0

Appendix D

Assumptions and Iterations Made for Initial Models

In this Appendix, the whole process regarding the development of the initial models, from Chapter 3, is explained, detailing the assumptions and iterations made for each study.

Study 1

This study lacks some important data required to build a comprehensive model. Despite this, an attempt was made to develop a validation model based on the available information for two primary reasons: the study incorporates heat modeling outside the absorber domain, including air heating, and accounts for convection and radiation losses, distinguishing it from other studies. Consequently, several iterations were performed to obtain a model similar to Study 1.

The absence of key properties posed a significant challenge in achieving comparable results. The absorber material is SiC, with permittivity (real and imaginary parts) provided as a function of temperature. This property was introduced in the model using an analytic function, with temperature as the argument. While permeability is known to be zero, other properties such as electrical conductivity, density, thermal conductivity, and heat capacity are not disclosed. Additionally, the base material is identified as porous alumina, but its properties are not specified. Initially, properties from Study 2 at 20 °C (Appendix C) were used.

To model heat losses from the absorber to the air, the *Heat Transfer in Solids Interface* was replaced with the *Heat Transfer in Solids and Fluids Interface*. In the first iteration, *convectively enhanced conductivity* was used to approximate natural convection within the microwave oven. This feature takes into account convective heat flux by enhancing the fluid thermal conductivity, multiplying it by the Nusselt number. This dimensionless number corresponds to the ratio of convective heat transfer to conductive heat transfer, and therefore characterizes the convection within a fluid. It can be obtained through different correlations, depending on the geometry that is being taken into account. In this case the geometry was approximated by an horizontal cavity heated from below. Although not an exact match, as the heated surfaces are from the absorber and not from the cavity itself, this approximation was considered reasonable.

Radiation was modeled using a *Surface-to-Surface Radiation Interface*. This feature treats thermal radiation as an energy transfer between boundaries and external heat sources, considering the medium transparent to radiation. All the boundaries were defined with a diffusive surface boundary condition, which reflect radiation uniformly in all directions, assuming that no radiation is transmitted through the surface. The heat transfer on the boundary is defined as the difference between the incident irradiation and the emissive power by the boundary.

The electric displacement field model is another important concept in electromagnetic simulations. The electric displacement field, also denoted as electric flux density (equation A.5), is a vector field that represents how electric fields interact with materials. As seen in equation A.5, this quantity will depend on the definition of the permittivity of the material. This parameter can be characterized in different ways, depending on if its imaginary part is zero, accounts for polarization losses only, or is composed by the contribution of both conduction and polarization losses. When the relative permittivity also accounts for conduction losses, the electrical conductivity of the material in the electric displacement field model needs to be defined as zero, preventing from taking these losses into account twice. Equation A.41 shows that if the permittivity of the material accounts for polarization and conduction losses, the electrical conductivity is not used to calculate the electromagnetic power loss.

For this model, given the real and imaginary parts of relative permittivity (ϵ_r' and ϵ_r'') of SiC, the available models to represent the relative permittivity in the electric displacement field model are the *Dielectric Loss Model* and the *Loss Tangent, Dissipation Factor Model*. However, the first considers that ϵ_r'' represents only the polarization losses, whereas the conduction losses are defined through the electrical conductivity. As ϵ_r'' of SiC already incorporates both types of losses, the correct electric displacement field model definition in this case is the *Loss Tangent, Dissipation Factor Model*, which sets conductivity as zero to overcome this issue.

The results revealed a significant deviation in electric field distribution and a maximum power loss value nine times higher than reported in the study. To address these discrepancies, multiple iterations were conducted regarding electromagnetic properties not documented in the study, that could affect these values, which are the electrical conductivity and the relative permittivity of alumina (σ_{alumina} and $\epsilon_{r,\text{alumina}}$).

A parametric sweep, varying only the electrical conductivity while holding other variables constant, showed minimal impact on the electric field. However, the relative permittivity of alumina significantly influenced the spatial distribution of this parameter. Adjusting ϵ_r from 1 to 4.5, it was determined that a relative permittivity of 1 produced the most similar electric field distribution within the cavity, as illustrated in Figure D.1, which compares this results with Study 1. Electrical conductivity was assumed to be the same as in Studies 2 and 3, given its negligible effect and the low conductivity of porous alumina. Despite these updates, the maximum power loss remained five times higher than the result from Study 1.

Due to these higher values of power loss, more energy is being absorbed by the material, naturally leading to higher temperatures. However, the temperature distribution also differed significantly from Study 1. To address this, the modeling of natural convection was refined using

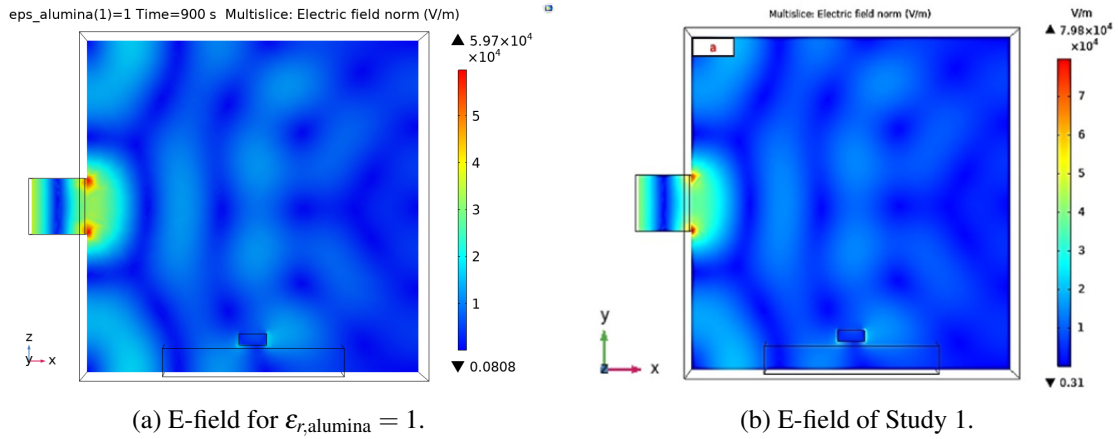


Figure D.1: Electric field distribution obtained with $\epsilon_{r,alumina} = 1$ (a) and from Study 1 (b).

a more realistic and computationally intensive approach. This involved incorporating a *Laminar Flow Interface* to accurately model the laminar airflow within the cavity and its associated buoyancy effects resulting from heat transfer from the absorber. Even though this approach is more realistic, the associated temperature results revealed to have more discrepancies compared to Study 1. The obtained absorber's maximum temperature was 75 % higher than in Study 1, and the spacial distributions difference is shown in Figure D.2. This leads to the conclusion that this was not the approach from the study, indicating that the solution obtained by the authors might be less accurate.

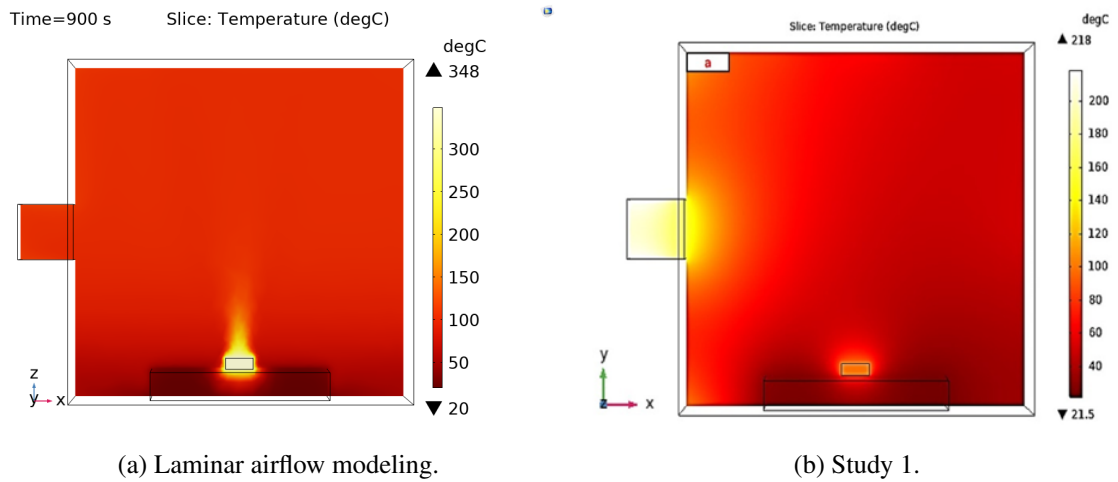


Figure D.2: Temperature distribution obtained with laminar airflow modeling (a) and from Study 1 (b).

The final results, considering again *convectively enhanced conductivity* to model convection, are presented and analysed in Section 3.4. To obtain these results, the mesh used was compared to the one used in Study 1, comparing the mesh type and size, number of elements, average element quality and maximum growth rate, as shown in Table D.1. The mesh used is identical to Study 1, with an even higher number of elements.

Table D.1: Mesh comparison between the developed model and Study 1

Model	Mesh Type	Mesh Size	Number of Elements	Avg. Element Quality	Max. Growth Rate
Study 1	Free tetrahedral	Extremely finer	1045401	0.6675	1.30
This Study	Free tetrahedral	Extremely finer	1369248	0.6626	1.30

Study 2

As detailed in chapter 3, Study 2 provided almost all of the required information regarding the simulation setup. However, the lack of some information mentioned in section 3.3.1, can still impact the results.

Examining the properties of SiC specified in Appendix C, it is evident that the relative permittivity is given a real value, implying that the imaginary part is zero. Therefore, dielectric losses are solely defined by the resistive losses due to the effect of conductivity, and polarization losses are not considered. Given this material definition, it is apparent that the natural choice for the electric displacement field model is the *Relative Permittivity Model*, which allows the attribution of the real part of relative permittivity and electrical conductivity of the material for solving Equation A.26, and sets the imaginary part of relative permittivity as zero.

The waveguide was assumed to be positioned at half length of the cavity, and its top surface was placed 10 mm below the top surface of the cavity.

Glass plate dimensions were assumed to be: 0.4 m of diameter and 0.02 m of height. Since glass is a poor electric conductor, conductivity was considered zero. Study 2 also mentions that dielectric loss factor of glass is negligible, so the imaginary part of relative permittivity was assumed to be zero. As glass is a non-magnetic material, permeability was set to 1.

The only property of the glass plate that still needed an attributed value was the real part of relative permittivity (ϵ_r'). A parametric sweep for ϵ_r' was performed, keeping all the other variables constant, and a final value of 2.52 was selected for this parameter. At this value of ϵ_r' , the results revealed to be closer to the ones from the study.

Mesh is also compared for this model with the respective study, as presented in Table D.2, which shows that meshes from the two models are identical.

Table D.2: Mesh comparison between the developed model and Study 2

Model	Mesh Type	Mesh Size	Number of Elements	Avg. Element Quality	Max. Growth Rate
Study 2	Free tetrahedral	Finer	49882	0.6638	1.40
This Study	Free tetrahedral	Finer	49554	0.6640	1.40

Study 3

Study 3 is almost complete in terms of information regarding the setup in COMSOL. Despite electric displacement field model not being specified, similarly to Study 2, it can be deducted by examining the properties definition of SiC (Appendix C). In this case, relative permittivity is defined by a real part (ϵ'_r) and a loss tangent ($\tan \delta$). Electrical conductivity does not have any attributed value, giving the idea that it will not be necessary.

With these properties defined, the most evident choice for the electric displacement field model is the *Loss Tangent, Dissipation Factor Model*, which sets electrical conductivity as zero and the losses are defined through the loss tangent only. Although it may seem that we are disregarding resistive losses by not considering conductivity, these losses are already contemplated in the loss tangent value, which, along with ϵ'_r , define the imaginary part of permittivity (ϵ''_r), that includes both polarization and conduction losses.

Mesh from the developed model is compared to Study 3, as shown in Table D.3, in terms of mesh type, maximum element size, number of elements and average element quality. This model used a higher number of elements and achieved a higher average element quality than Study 3.

Table D.3: Mesh comparison between the developed model and Study 3

Model	Mesh Type	Max. Element Size	Number of Elements	Avg. Element Quality
Study 3	Free tetrahedral	$\frac{1}{8} \times \lambda$ - cavity and waveguide; 2 and 3 mm - SiC and alumina	173883	0.6633
This Study	Free tetrahedral	$\frac{1}{8} \times \lambda$ - cavity and waveguide; 2 and 3 mm - SiC and alumina	237157	0.6676

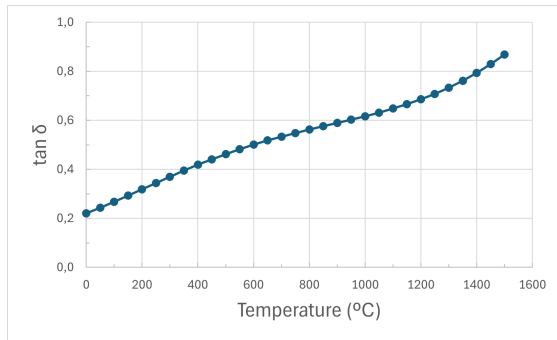
Appendix E

Absorption Parameters Calculated with Study 1 Material Properties

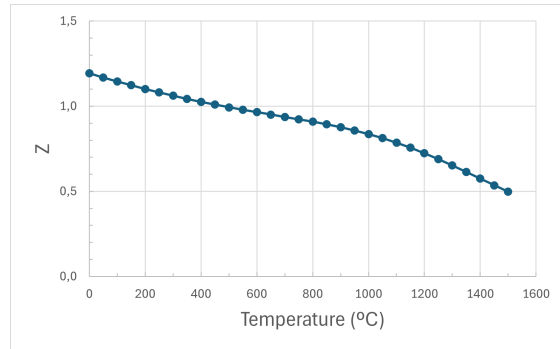
In Study 1, the relative permittivity (both real and imaginary parts) of SiC is detailed, as shown in Appendix C. Utilizing these temperature-dependent properties, the absorption parameters were calculated and plotted over a temperature range from 0 to 1500 °C.

The results obtained were consistent with those reported in the study, thereby validating the calculations performed for each parameter. This validation supports the subsequent use of these parameters for material comparison.

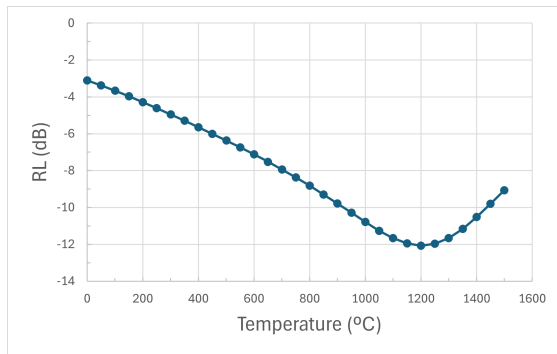
Analysing Figure E.1c, it becomes clear that the best values of reflection loss (RL), more negative values, were obtained for 1200 °C, showing that a further increase in temperature continues to increase the loss tangent but also increases reflection, which is not desired for microwave energy absorption. It is also visible that as attenuation increases, Figure E.1d, penetration depth decreases, Figure E.1e, as these variables are inversely proportional.



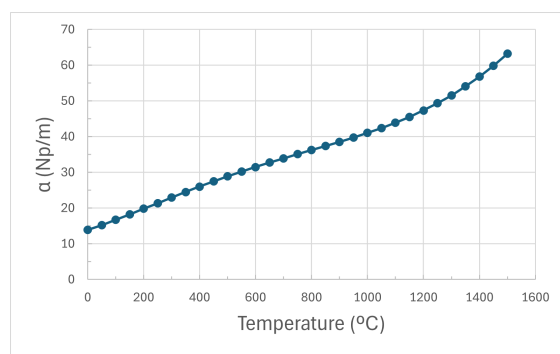
(a) Loss tangent ($\tan \delta$) variation with temperature for SiC.



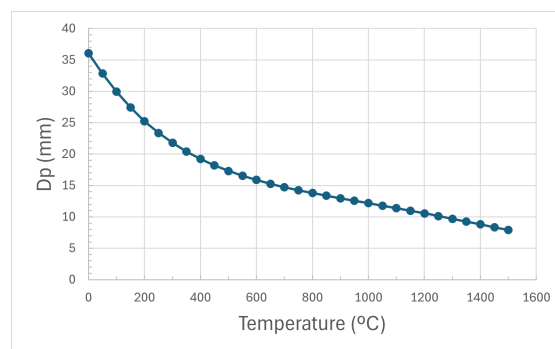
(b) Degree of impedance matching (Z) variation with temperature for SiC.



(c) Reflection loss (RL) variation with temperature for SiC.



(d) Attenuation (α) variation with temperature for SiC.



(e) Penetration depth (D_p) variation with temperature for SiC.

Figure E.1: Absorption parameters calculated with Study 1 material properties.

Appendix F

Comparison Between Obtained Results in Initial Models and Reference Models

In this appendix, a more detailed comparison is presented between the obtained results and the literature results for the spatial distributions of relevant parameters.

Study 1

The comparison between the results obtained in the developed model and the results achieved in Study 1 is shown in Figure [F.1](#). Although the spatial distributions are similar, the magnitude of the parameters exhibits significant differences.

Study 2

Figures [F.2](#) and [F.3](#) show the similarity between the results obtained in the developed model and the results achieved in Study 2, in terms of fields distributions. Even though there are visible differences, they are not significant.

Study 3

Figure [F.4](#) shows the comparison between the results obtained in the developed model and the results achieved in Study 3. As it can be seen in the Figure, spatial distributions of electric field, temperature, and power loss density, at the end of simulation time, are very similar. Maximum electric field norm value is considerably different, although, as explained in section [3.4.3](#), this difference is only significant near the top surface of the absorber, where the electric field is maximum.

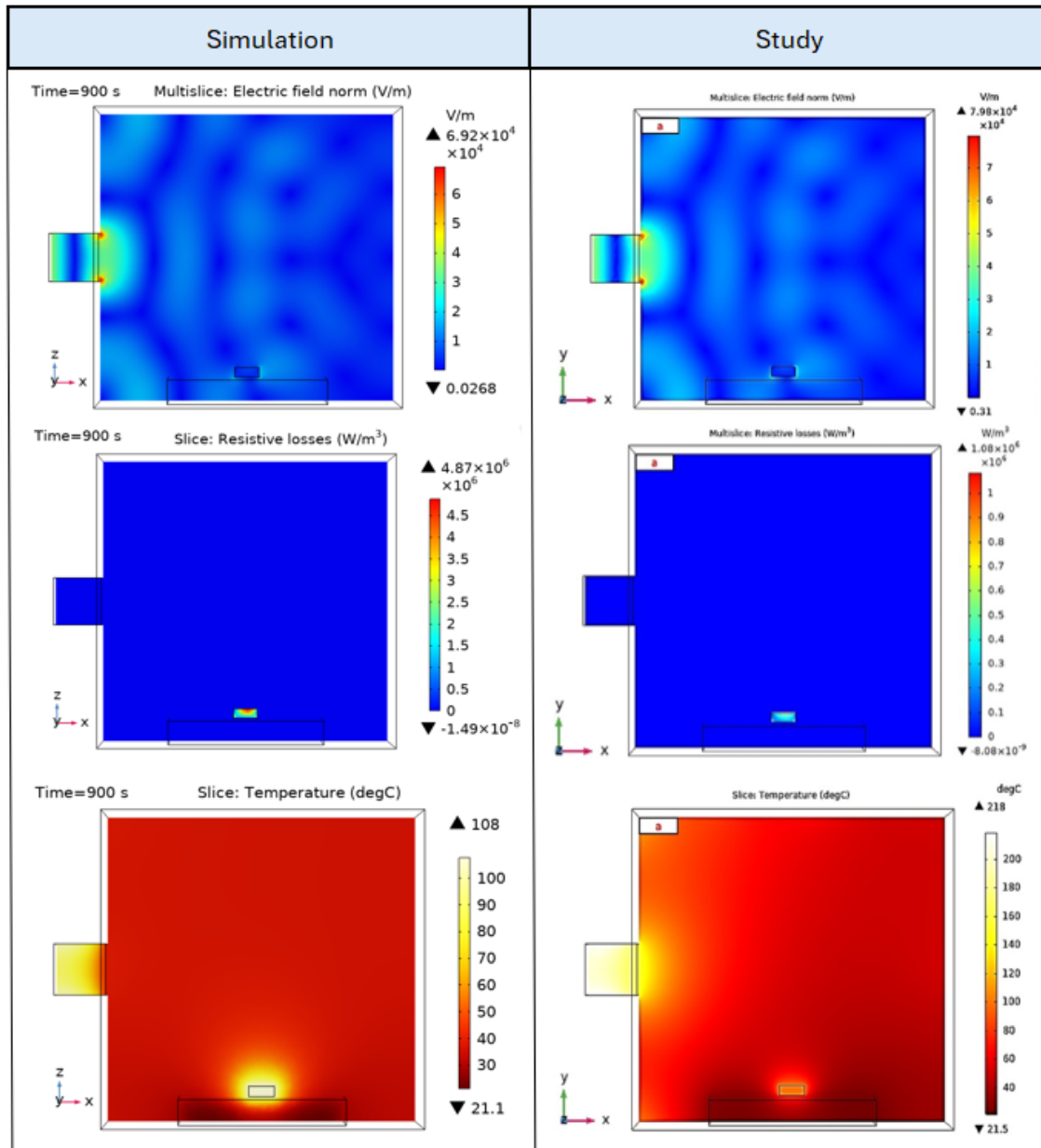


Figure F.1: Comparison of electric field, resistive loss, and temperature distributions, between the developed model and Study 1 model.

	Study	Simulation
0 sec	T=20°C	T=20°C
60 sec	T=156.28°C	T=151°C
120 sec	T=263.83°C	T=258°C
180 sec	T=361.86°C	T=355°C
240 sec	T=453.81°C	T=446°C
300 sec	T=542.05°C	T=534°C

Figure F.2: Comparison of temperature field distribution and maximum temperature between the developed model and Study 2 model.

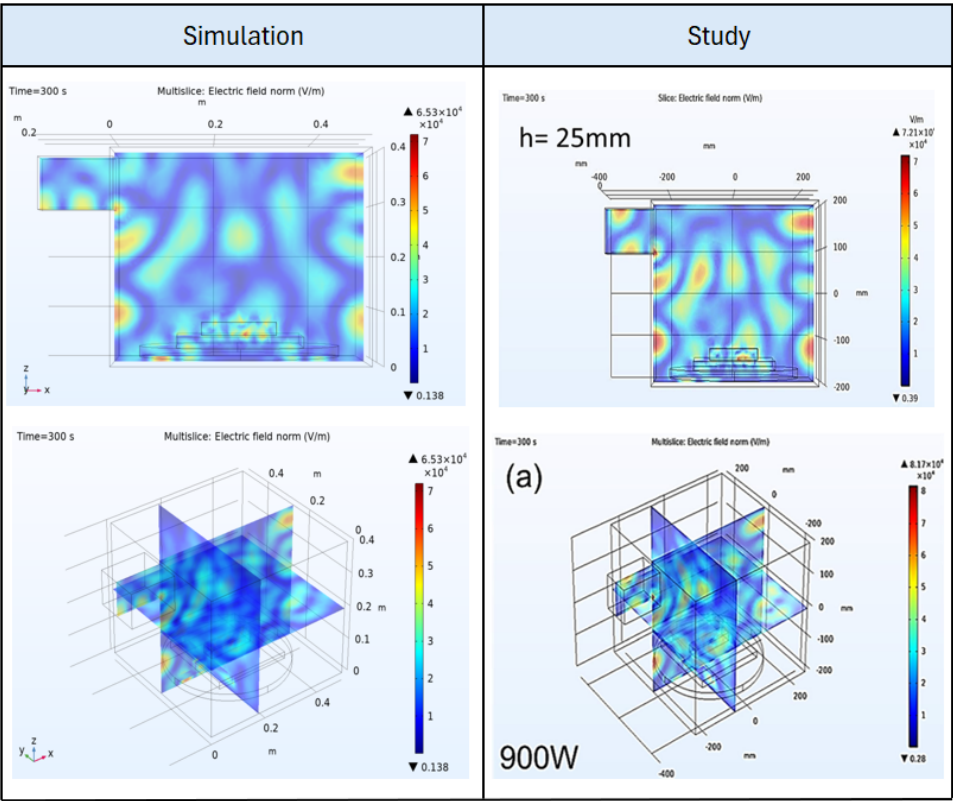


Figure F.3: Comparison of electric field distribution between the developed model and Study 2 model.

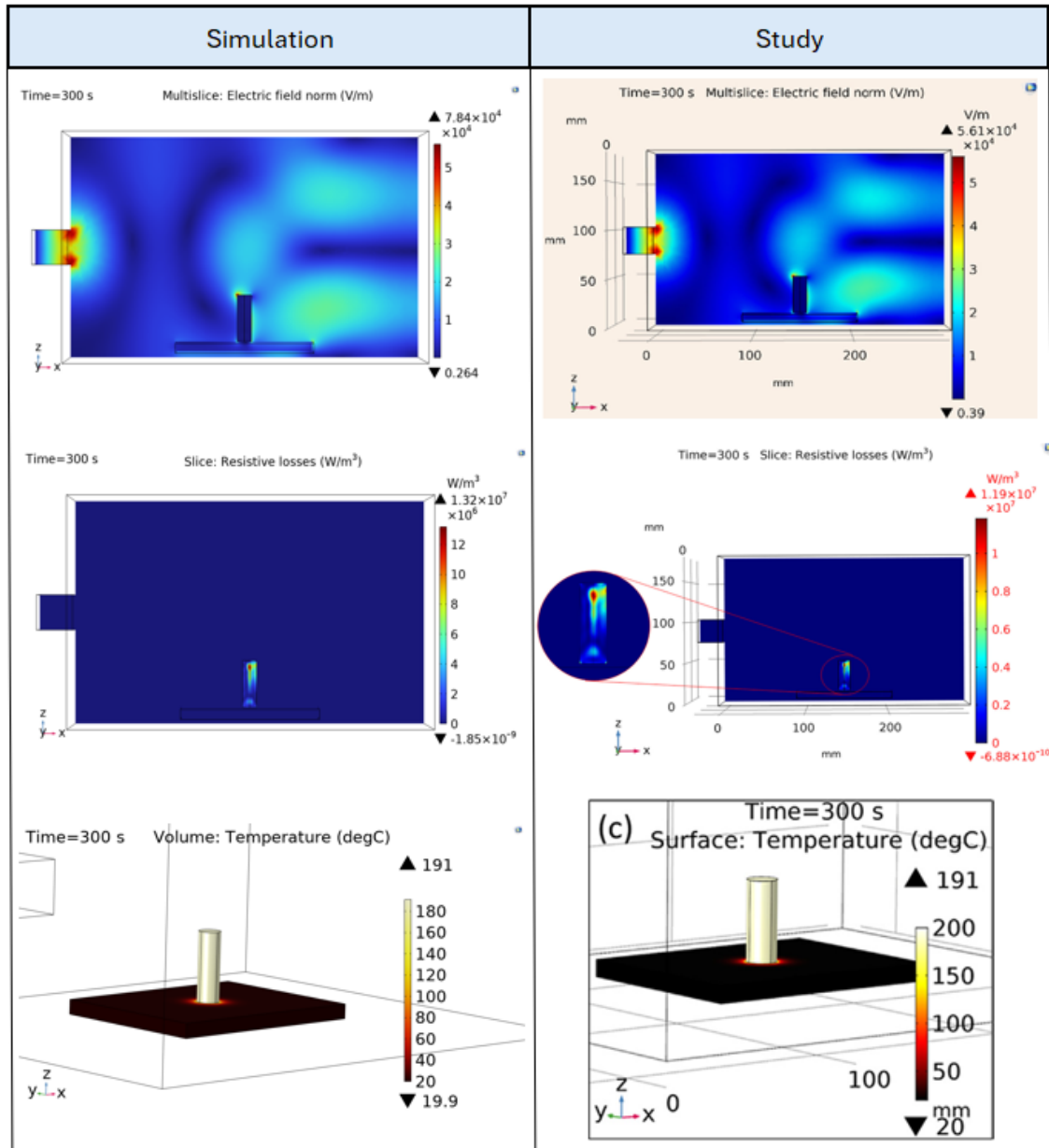


Figure F.4: Comparison of electric field, power loss, and temperature distributions, between the developed model and Study 3 model.

Appendix G

3D Designs of Microwave Anti-icing System Using Other Airfoils

As an alternative blade profile, it was considered a NACA 2412 airfoil. With a lower thickness, it would represent a section closer to the blade tip, therefore with less housing space.

Figure G.1 shows the representation of the microwave anti-icing system using slotted waveguides, for the respective geometry. The configuration with magnetrons along the blade's interior is shown in Figure G.2, with emission through the magnetron's output antenna (Figure G.2a), and emission through waveguide openings (Figure G.2b). The last case differs from the one presented for airfoil NACA 64-421, see section 4.2.2, as for that case it was considered emission through horn antennas. However, as this profile has a lower thickness, another possible design is presented, where the waveguide is coupled with the magnetron on its side (x -direction) rather than below it (z -direction) (Figure G.2b).

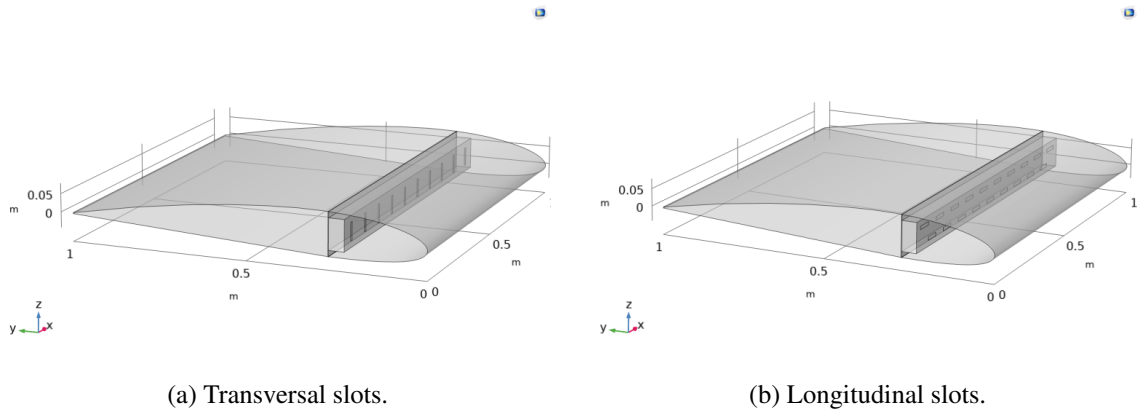
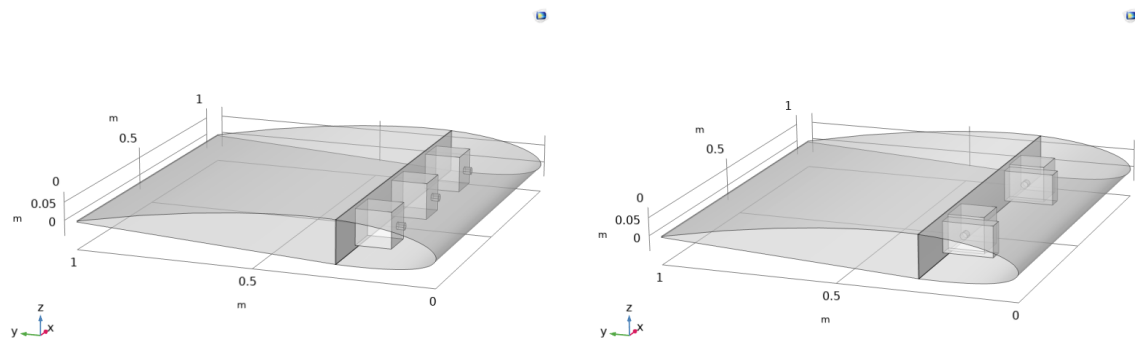


Figure G.1: Microwave transport and emission through slotted waveguides (airfoil NACA 2412).



(a) Emission through magnetron's output antenna.

(b) Emission through waveguide opening.

Figure G.2: Microwave generation and emission through magnetrons along the blade (airfoil NACA 2412).

Appendix H

EES Steady-state Model

Mathematical formulation

The goal of this steady-state model is to calculate the required power to keep the blade surface at least at a predefined temperature, T_{sup} , above 0 °C. With this approach, the minimum temperature that we consider acceptable to avoid icing can be set. Basically, it is needed to calculate the power loss due to convection and radiation. The reason for this is that if the power supplied equals the power loss at a given temperature, then equilibrium is reached at that temperature.

Naturally, convection and radiation will depend on the atmospheric conditions. Convective heat flux, per meter square, $\dot{q}_c$, can be defined by the following expression [88]:

$$\dot{q}_c = h \cdot (T_{sup} - T_{\infty}), \quad (\text{H.1})$$

where h is the convection coefficient, and T_{∞} is the air temperature outside the thermal boundary layer - region where there are temperature gradients between the fluid and the surface.

If both T_{sup} and T_{∞} are specified, to define the convection loss it is only necessary to obtain h . Heat flux on any surface in contact with a fluid can be given by [88]:

$$\dot{q}_c = -k_f \left. \frac{\partial T}{\partial y} \right|_{y=0}, \quad (\text{H.2})$$

where k_f is the thermal conductivity of the fluid, and $\left. \frac{\partial T}{\partial y} \right|_{y=0}$ represents the temperature gradient on the surface. Combining equations H.1 and H.2, we obtain [88]:

$$h = \frac{-k_f \left. \frac{\partial T}{\partial y} \right|_{y=0}}{T_{sup} - T_{\infty}}. \quad (\text{H.3})$$

As the thermal boundary layer increases with the increasing distance from the leading edge, x , the thermal gradients inside this layer decrease. Therefore the temperature gradient on the surface decreases with increase in x . Considering $(T_{sup} - T_{\infty})$ constant, h , and consequently $\dot{q}_c$, decrease with increasing x [88].

For this reason, if it is intended to calculate the required power, this should be calculated for the critical region: the leading edge. If the same power is supplied to the other points of the blade cross-section, than the surface temperature at those points is expected to be higher than the leading edge value. This analysis does not take into account the acceleration effects on the airflow around the airfoil, caused by pressure differences.

To approximate the leading edge, we can simplify the geometry by a flat plate of small dimensions (20 mm of length in the flow direction) and calculate the average convection coefficient. This value can be estimated in two ways: considering constant surface temperature, or considering constant heat flux on the surface. As the temperature will change across the surface, the expression for constant heat flux was considered. This is also an approximation, as the heat flux supplied by the microwaves will actually change throughout the blade surface. Nevertheless, generalising for a constant supplied heat flux by an anti-icing system, the average convection coefficient, h_m , for a flat plate, can be calculated by [93]:

$$h_m = \frac{3}{2} \cdot 0.453 \cdot Pr \cdot \frac{1}{3} \sqrt{\frac{V_r \cdot L_p}{\nu}} \cdot \frac{k_f}{L_p}, \quad (\text{H.4})$$

where Pr is the Prandtl number of the fluid, V_r is the fluid velocity relative to the surface, L_p is the length of the flat plate and ν is the kinematic viscosity of the fluid.

To calculate the radiation losses, $\dot{q}_{rad}$, the following expression is considered [93]:

$$\dot{q}_{rad} = e \cdot \sigma_s \cdot (T_{sup}^4 - T_{\infty}^4), \quad (\text{H.5})$$

where e represents the surface emissivity, σ_s the Stefan-Boltzmann constant, and the temperatures are defined in Kelvin.

Simulation setup

Applying the mathematical formulation described above, it is possible to calculate $\dot{q}_c$ and $\dot{q}_{rad}$. In the setup shown in Figures H.1 and H.2, T_{sup} is defined as 1 °C, T_{∞} is equal to -20 °C, surface emissivity is set as 0.5, and the wind relative velocity is varied from 5 to 90 m/s. These values can be changed to obtain results for different conditions.

Figure H.1 shows the equations used in EES, and Figure H.2 shows the parametric table which allows the calculation of the results for the defined range of wind relative velocity. The last figure only presents the first rows of the parametric table.

Formatted Equations

```

Fluid$ = 'Air_ha'
P = 101,3 [kPa]
T_sup = 1 [C]
T_inf = -20 [C]

Constant heat flux

T_média = (T_sup + T_inf) / 2

k = k (Air_ha ; T = T_média ; P = P)
v = KinematicViscosity (Air_ha ; T = T_média ; P = P)
Pr = Pr (Air_ha ; T = T_média ; P = P)
L_placa = 0,02 [m]

according to Holman 8Ed. pg242

q_w = 3 / 2 * hq_L * (T_sup - T_inf)  average convection coefficient is 3/2 of the local for constant q
hq_L = 0,453 * Pr^(1/3) * sqrt(Veloc * L_placa / v) * k / L_placa  this is the expression of convection coefficient for constant heat flux

q_rad = epsilon * 5,670E-08 [W/m^2-K^4] * (T_sup,K^4 - T_inf,K^4)
epsilon = 0,5

T_sup,K = ConvertTemp (C ; K ; T_sup)
T_inf,K = ConvertTemp (C ; K ; T_inf)

```

Figure H.1: Equations used in EES steady-state model.

Parametric Table

Table 1

	1	2	3	4	5	
	$\dot{q}_w$ [W/m ²]	$\dot{q}_{rad}$ [W/m ²]	T_{∞} [C]	T_{sup} [C]	Veloc [m/s]	
Run 1	1347	43,72	-20	1	5	
Run 2	1404	43,72	-20	1	5,427	
Run 3	1458	43,72	-20	1	5,854	
Run 4	1510	43,72	-20	1	6,281	
Run 5	1560	43,72	-20	1	6,709	
Run 6	1609	43,72	-20	1	7,136	
Run 7	1657	43,72	-20	1	7,563	
Run 8	1703	43,72	-20	1	7,99	
Run 9	1748	43,72	-20	1	8,417	
Run 10	1792	43,72	-20	1	8,844	
Run 11	1834	43,72	-20	1	9,271	
Run 12	1876	43,72	-20	1	9,698	
Run 13	1917	43,72	-20	1	10,13	
Run 14	1957	43,72	-20	1	10,55	
Run 15	1996	43,72	-20	1	10,98	
Run 16	2035	43,72	-20	1	11,41	
Run 17	2073	43,72	-20	1	11,83	
Run 18	2110	43,72	-20	1	12,26	

Figure H.2: Parametric table used in EES steady-state model.

Appendix I

Selected Microwave Absorbing Materials Properties

Table I.1 shows the properties used in COMSOL simulations for each of the selected microwave absorbing material. The cells highlighted in green indicate the properties which were estimated due to lack of available information. These values were estimated using the rule of mixtures for composites, which uses the properties of the isolated materials that form the composite, multiplied by the volume fraction of each material. Since the material composition of Eccosorb BSR-1 is not available, a value of 1000 J/(kg.K) was assumed.

Table I.1: Properties of the selected microwave absorbing materials

Materials	(NBSiC)p	MWCNT-PP	CCFRP	MWCNT-epoxy	Eccosorb BSR-1
Density	2690 [94]	888 [95]	1223 [96, 97]	1254 [95, 98]	4200 [99]
Thermal Conductivity	32 [94]	0.28 [95]	1.49 [96, 97]	2.60 [100]	0.87 [99]
Heat Capacity	700 [101, 102]	1685 [103, 104]	1563 [96, 97]	1089 [98, 104]	1000
Relative Permittivity - Real	9.31 [86]	10.25 [105]	7.53 [97]	7.98 [106]	19.097 [107]
Relative Permittivity - Imaginary	2.53 [86]	3.01 [105]	4.05 [97]	0.78 [106]	0.947 [107]
Relative Permeability - Real	1 [86]	1.03 [105]	1 [97]	1.36 [106]	3.634 [107]
Relative Permeability - Imaginary	0 [86]	0.055 [105]	0 [97]	0.116 [106]	1.887 [107]

Appendix J

RL and Z Variations with Thickness for the Selected Materials

Figures J.1, J.2, J.3, J.4, and J.5 show the reflection loss (RL) and degree of impedance matching (Z), calculated with equations A.57 and A.54, for (NBSiC)p, MWCNT-PP, CCFRP, MWCNT-epoxy, and Eccosorb BSR-1, respectively.

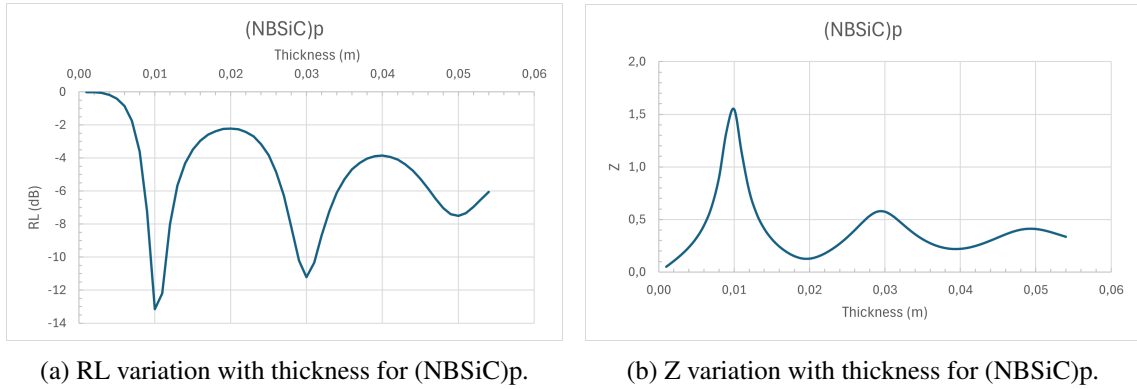


Figure J.1: RL and Z variation with thickness for (NBSiC)p.

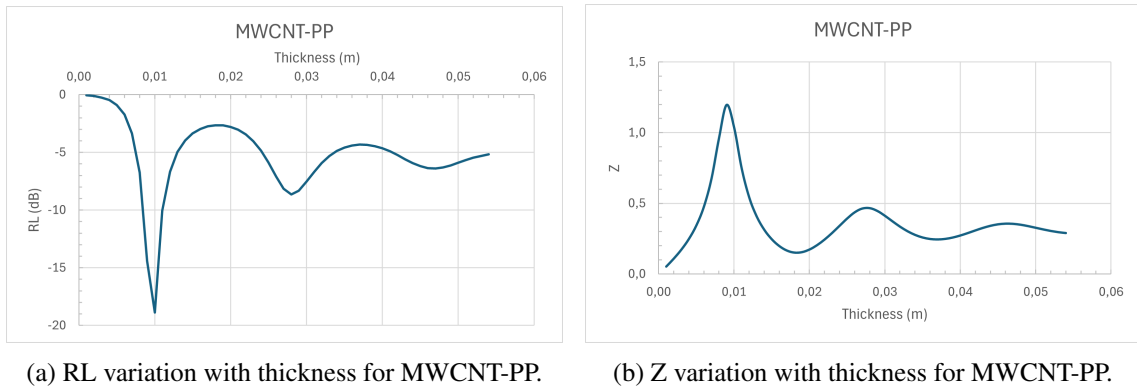
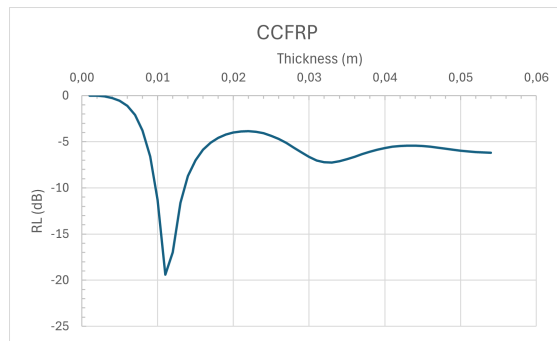
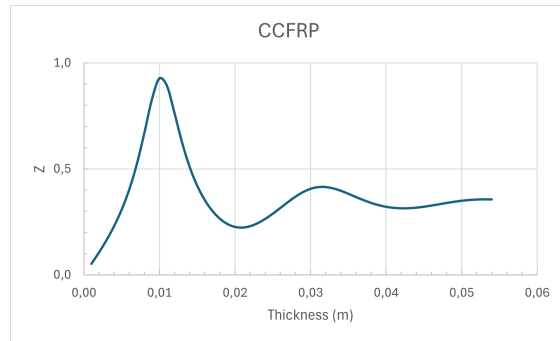


Figure J.2: RL and Z variation with thickness for MWCNT-PP.

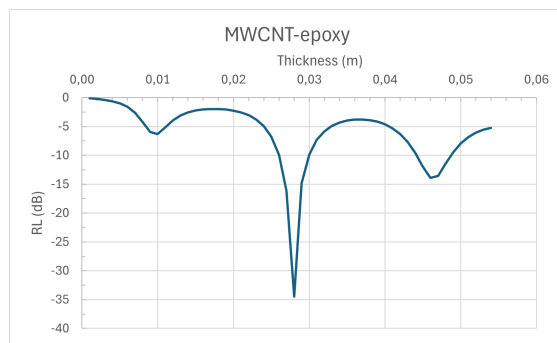


(a) RL variation with thickness for CCFRP.

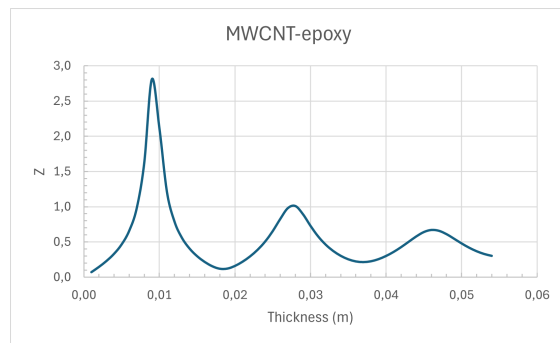


(b) Z variation with thickness for CCFRP.

Figure J.3: RL and Z variation with thickness for CCFRP.

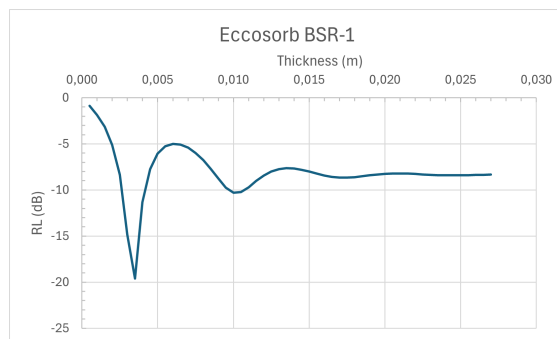


(a) RL variation with thickness for MWCNT-epoxy.

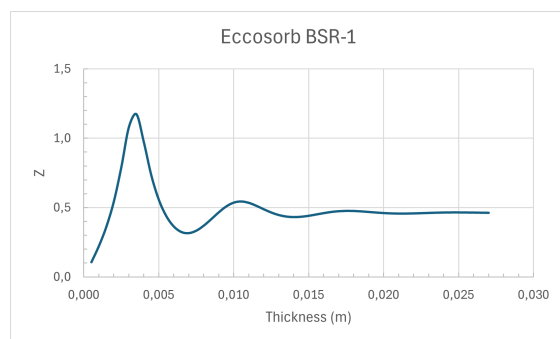


(b) Z variation with thickness for MWCNT-epoxy.

Figure J.4: RL and Z variation with thickness for MWCNT-epoxy.



(a) RL variation with thickness for Eccosorb BSR-1.



(b) Z variation with thickness for Eccosorb BSR-1.

Figure J.5: RL and Z variation with thickness for Eccosorb BSR-1.

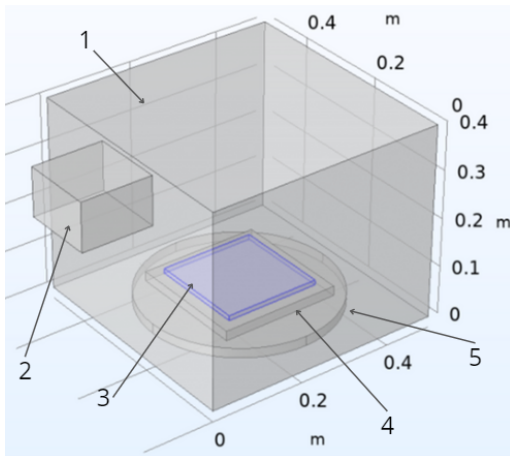
Appendix K

Adaptation of Initial Models - geometries

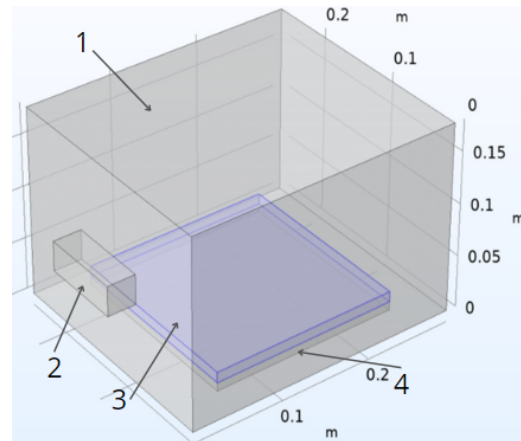
Figure [K.1](#) shows the geometry of the different models used to adapt the initial validated models in Chapter 3, into a Flat Plate Model of the microwave absorbing layer.

Figures [K.1a](#) and [K.1b](#) present the geometries used in the first modification, starting from the validated models based on Study 2 and Study 3, respectively.

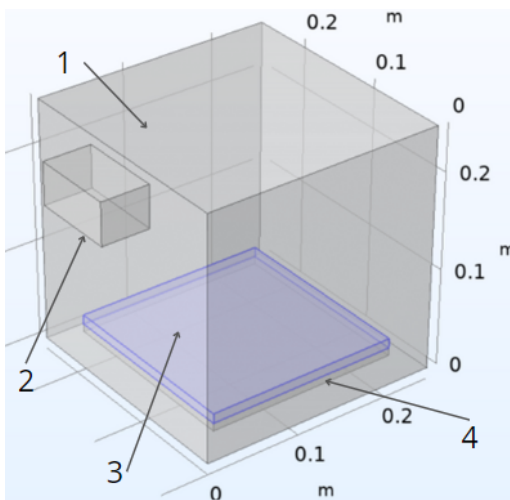
Figures [K.1e](#) and [K.1f](#) include in the legend the boundary conditions used on the walls, as it represents the main modification between the two studies. IBC refers to an Impedance Boundary Condition and SBC refers to a Scattering Boundary Condition.



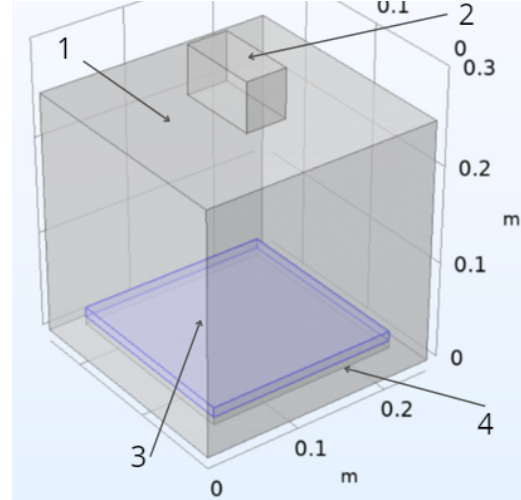
(a) 1st Flat Plate Model - Study 2. 1 - cavity; 2 - waveguide; 3 - absorber; 4 - base; 5 - glass plate.



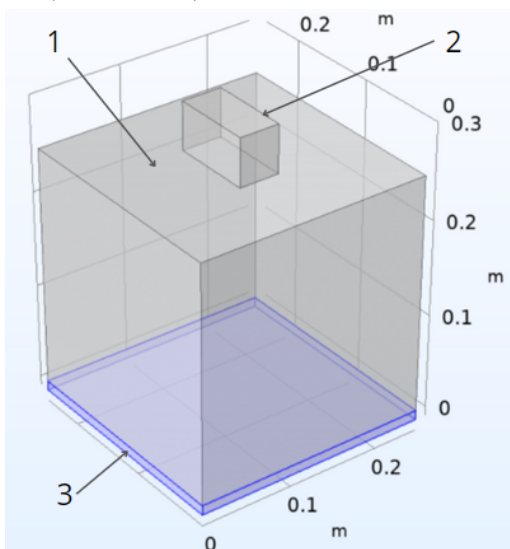
(b) 1st Flat Plate Model - Study 3. 1 - cavity; 2 - waveguide; 3 - absorber; 4 - base.



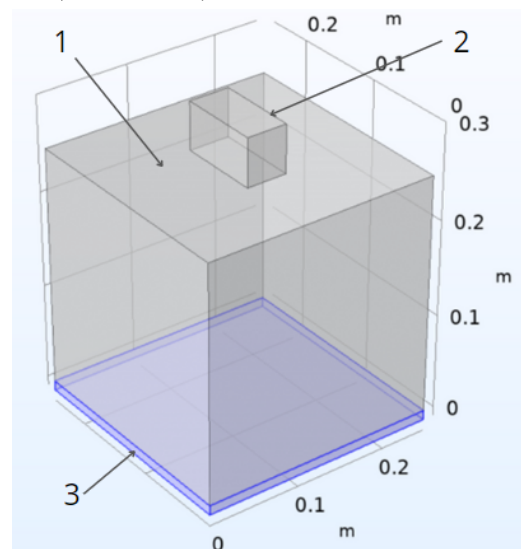
(c) 2nd Flat Plate Model. 1 - cavity; 2 - waveguide; 3 - absorber; 4 - base.



(d) 3rd Flat Plate Model. 1 - cavity; 2 - waveguide; 3 - absorber; 4 - base.



(e) 4th Flat Plate Model. 1 - cavity with IBC; 2 - waveguide; 3 - absorber with SBC.



(f) 5th Flat Plate Model. 1 - cavity with SBC; 2 - waveguide; 3 - absorber with SBC.

Figure K.1: Flat Plate Models geometry. The absorber is highlighted in blue.

Appendix L

Mesh Refinement Analysis for The Developed Models in This Dissertation

As already mentioned in Section 3.3.1, a very important parameter of any numerical simulation is the mesh used to discretize the geometry, allowing to solve the problem at discrete points in space. As this mesh is refined, the solution tends to more accurate results. Therefore, to obtain accurate results from the COMSOL models, the model must be re-solved with progressively finer meshes, comparing the results. When the results converge and there is no significant change after refining the mesh, then the mesh is no longer influencing the results of the simulation and does not need to be refined further.

This appendix serves to present the mesh refinement studies performed for all models developed in Chapter 5.

L.1 Adaptation of Initial Models

For the adaptation of initial models, described in Section 5.1.1, the first two models (First and Second Flat Plate Models) used the same mesh from the initial models based on Study 2 and Study 3, which are detailed in Appendix D.

For the Third, Fourth and Fifth Flat Plate Models, it was used a user-controlled mesh with a free tetrahedral mesh type and an element size calibrated for general physics. It was selected a predefined element size, which, from the less refined to the more refined mesh, come as: extremely coarse, extra coarse, coarser, coarse, normal, fine, finer, extra fine and extremely fine.

Tables L.1, L.2, and L.3 show the mesh refinement studies performed for these three models. The results were analysed only for MWCNT-PP as the absorber, since the geometry for the other two materials is similar. These studies compare the results of interest, for the final instant of simulation time, from the model with different mesh sizes. The mesh was refined until all the results converge, with the final mesh used in the model being highlighted in green.

Table L.1: Mesh refinement study for the 3rd Flat Plate Model

	Predefined element size			Nr. Of elements	Avg. element quality	Max. T (°C)	Avg. T (°C)	Max. E-field norm (V/m)	Avg. E-field norm (V/m)	Max. Power loss (W/m ³)	Avg. Power loss (W/m ³)	Power loss (W)
	Cavity + Waveguide	Base	Absorber									
Mesh 1	finer	extra fine	extra fine	66630	0,6606	574,94	252	4,29E+04	4737,7	4,53E+06	1,16E+06	462,87
Mesh 2	extra fine	extra fine	extra fine	227080	0,6616	577,36	253,01	5,61E+04	4740,5	4,53E+06	1,16E+06	464,87
Mesh 3	extremely fine	extremely fine	extremely fine	780461	0,6700	577,94	253,11	5,71E+04	4740,9	4,53E+06	1,16E+06	464,98

Table L.2: Mesh refinement study for the 4th Flat Plate Model

	Predefined element size		Nr. Of elements	Avg. element quality	Max. T (°C)	Avg. T (°C)	Max. E-field norm (V/m)	Avg. E-field norm (V/m)	Max. Power loss (W/m ³)	Avg. Power loss (W/m ³)	Power loss (W)
	Cavity + Waveguide	Absorber									
Mesh 1	finer	extra fine	61971	0,661	393,89	78,687	3,79E+04	4349,3	2,94E+06	2,93E+05	182,95
Mesh 2	extra fine	extra fine	212691	0,6602	396,13	79,141	4,22E+04	4355,9	2,98E+06	2,95E+05	184,36
Mesh 3	extremely fine	extremely fine	765267	0,6637	396,34	79,451	4,23E+04	4356,2	2,98E+06	2,95E+06	184,81

Table L.3: Mesh refinement study for the 5th Flat Plate Model

	Predefined element size		Nr. Of elements	Avg. element quality	Max. T (°C)	Avg. T (°C)	Max. E-field norm (V/m)	Avg. E-field norm (V/m)	Max. Power loss (W/m ³)	Avg. Power loss (W/m ³)	Power loss (W)
	Cavity + Waveguide	Absorber									
Mesh 1	finer	extra fine	85340	0,6722	81,255	45,921	4,75E+04	2701,9	4,37E+05	1,29E+05	51,714
Mesh 2	extra fine	extra fine	279294	0,6653	80,457	45,608	6,70E+04	2690,7	4,35E+05	1,28E+05	51,09
Mesh 3	extremely fine	extremely fine	830569	0,6635	80,367	45,576	6,71E+04	2692,4	4,35E+05	1,28E+05	51,01

L.2 MAL Model

In the MAL Model, described in Section 5.1.2, a user-controlled mesh with a free tetrahedral mesh type was used, calibrated for general physics. The maximum element size was varied, keeping the minimum element size, growth rate, and curvature factor constant and equal to 4E-04, 1.35, and 0.3, respectively.

Table L.4 shows the mesh refinement study performed for this model with MWCNT-PP as the absorber. For the other two materials, the mesh used was the same as for MWCNT-PP, given the dimensions similarity. The mesh was refined by decreasing the maximum element size, until all the results of interest converge, with the final mesh used in the model being highlighted in green.

Table L.4: Mesh refinement study for the MAL Model

	Maximum element size		Nr. Of elements	Avg. element quality	Max. T (°C)	Avg. T (°C)	Max. E-field norm (V/m)	Avg. E-field norm (V/m)	Max. Power loss (W/m ³)	Avg. Power loss (W/m ³)	Power loss (W)
	MAL	Air									
Mesh 1	0,009	0,014	111735	0,6665	127,18	76,876	4,73E+04	1708,3	9,26E+05	3,13E+05	125,15
Mesh 2	0,007	0,012	193756	0,6725	125,49	76,831	5,16E+04	1709,2	8,70E+05	3,13E+05	125,05
Mesh 3	0,005	0,010	371342	0,6671	125,25	76,826	5,17E+04	1709,4	8,66E+05	3,13E+05	125,03

L.3 BMI Model

In the BMI Model, described in Section 5.1.3, a user-controlled mesh with a free tetrahedral mesh type was also used, calibrated for general physics. The maximum element size was decreased, keeping the minimum element size, growth rate, and curvature factor, constant and equal to 4E-04, 1.35, and 0.3, respectively.

Table L.5 shows the mesh refinement study performed for this model with MWCNT-PP as the absorber. Once again, for the other two materials, the mesh used was the same. The mesh was refined until all the results of interest converge, with the final mesh used in the model being highlighted in green.

Table L.5: Mesh refinement study for the BMI Model

	Maximum element size		Nr. Of elements	Avg. element quality	Max. T (°C)	Avg. T (°C)	Max. E-field norm (V/m)	Avg. E-field norm (V/m)	Max. Power loss (W/m3)	Avg. Power loss (W/m3)	Power loss (W)
	Blade	Air									
Mesh 1	0,014	0,014	100119	0,6605	126,61	45,51	4,19E+04	1073,9	2,16E+06	5,21E+05	209,55
Mesh 2	0,010	0,012	169828	0,6691	125,11	45,45	5,10E+04	1076,8	1,98E+06	5,10E+05	208,82
Mesh 3	0,006	0,010	332740	0,6692	125,05	45,42	5,12E+04	1077,1	1,97E+06	5,09E+05	208,58

L.4 2D Airfoil Model - Constant Convection Coefficient

In the 2D Airfoil Model with constant convection coefficient, described in Section 5.2, the mesh used was a user-controlled mesh with a free triangular mesh type calibrated for general physics. Since this is a 2D model, the number of mesh elements will be significantly reduced compared to the previous models. Therefore, the mesh can be refined without the necessity of introducing small gradual changes, as the computational effort with a very refined mesh is still not very significant. The maximum element size was decreased, keeping the minimum element size, growth rate, and curvature factor, constant and equal to 8E-05, 1.2, and 0.25, respectively. To mesh the layered materials (except the MAL), there were introduced 3 mesh elements per layer, and 10 mesh elements in the core material, which is thicker.

Table L.6 shows the mesh refinement study performed for this model with Eccosorb BSR-1 as the absorber. For the other two materials the mesh was modeled with the same setup, since Eccosorb BSR-1 is the thinner material and, consequently, requires the more refined mesh. The mesh was refined until all the results of interest converge, with the final mesh used in the model being highlighted in green.

L.5 2D Airfoil Model - CFD

In the 2D Airfoil Model with constant convection coefficient, described in Section 5.2, a user-controlled mesh with a free triangular mesh type was used. The CFD simulation requires a refined

Table L.6: Mesh refinement study for the 2D Airfoil Model with constant convection coefficient

	Maximum element size		Nr. Of elements	Avg. element quality	Max. T (°C)	Avg. T (°C)	Max. E-field norm (V/m)	Avg. E-field norm (V/m)	Max. Power loss (W/m ³)	Avg. Power loss (W/m ³)	Power loss (W/m)
	MAL	Air									
Mesh 1	0.022	0.041	11458	0.8363	86,735	28,033	1.01E+04	557.98	9,22E+06	1,43E+06	3891,5
Mesh 2	0.010	0.012	82862	0.8563	86,653	28,210	1.01E+04	558,27	8,06E+06	1,43E+06	3891,7

mesh, specially in the boundaries where the airflow will interact with the airfoil. Therefore, a boundary layer mesh with 8 layers was created, and attributed to the airfoil exterior boundaries (the blade surface). Additionally, a corner refinement was also applied to these boundaries. The mesh of the air domain corresponding to the airflow was calibrated for fluid dynamics, while the other domains were calibrated for general physics.

The maximum element size was varied for the airflow domain outside the PML, airflow inside the PML, MAL, and interior air. To mesh the layered materials (except the MAL), there were introduced 3 mesh elements per layer, and 10 mesh elements in the core material, which is thicker.

The minimum element size, growth rate, and curvature factor, were kept constant. For the interior air, the MAL, and the airflow inside the PML, these values corresponded to 4.6E-4, 1.3, and 0.3, respectively. For the airflow domain, outside the PML, these values were set to 0.04, 1.1, and 0.25, respectively.

Table L.7 shows the mesh refinement study performed for this model with Eccosorb BSR-1 as the absorber. For the other two materials the mesh was modeled with the same setup, since Eccosorb BSR-1 is the thinner material and, consequently, requires the more refined mesh. The mesh was refined until all the results of interest converge, with the final mesh used in the model being highlighted in green.

Table L.7: Mesh refinement study for the 2D Airfoil Model with CFD

	Maximum element size				Nr. Of elements	Avg. element quality	Max. T (°C)	Avg. T (°C)	Max. E-field norm (V/m)	Avg. E-field norm (V/m)	Max. Power loss (W/m ³)	Avg. Power loss (W/m ³)	Power loss (W/m)	Max. Velocity (m/s)
	Airflow	PML	MAL	Int. Air										
Mesh 1	2.90	0.012	0.003	0.016	62402	0.8597	81,453	27,102	1.01E+04	557.54	9,22E+06	1,43E+06	3891,5	82,390
Mesh 2	2.80	0.010	0.002	0.015	89936	0.8550	81,939	27,145	1.01E+04	558.26	8,06E+06	1,43E+06	3891,7	82,392

Appendix M

EES Transient Model

Mathematical formulation

In this model, it is intended to obtain the transient temperature variation of each layer in the microwave de-icing system. For that purpose, the blade laminate composition needs to be known, as well as specifying the absorber's material, thickness, and placement within the laminate.

The problem is solved by considering that the temperature of each layer is defined by the temperature at its center. Therefore, to obtain the temperatures of each layer, there is only need to develop heat balances for each, accounting for conduction between the adjacent layers, and boundary conditions on the inner and outer layers. The MAL should also include heat generated, considering that this power is absorbed by the MAL throughout its whole volume.

For a given layer i , with adjacent layers $i + 1$ and $i - 1$, the heat balance can be expressed by:

$$A \cdot \left[\frac{T_{i-1} - T_i}{\frac{d_{i-1}}{2 \cdot k_{i-1}} + \frac{d_i}{2 \cdot k_i}} \right] - A \cdot \left[\frac{T_i - T_{i+1}}{\frac{d_i}{2 \cdot k_i} + \frac{d_{i+1}}{2 \cdot k_{i+1}}} \right] = m_i \cdot c_{p_i} \cdot \frac{dT_i}{dt}, \quad (\text{M.1})$$

where A is the area considered for the blade heated surface, and T , d , k , m and c_p represent the temperature, thickness, thermal conductivity, mass, and heat capacity of the correspondent layer, respectively.

For the MAL, the same equation can be applied, adding the heat generated inside by microwave absorption. Considering $\dot{q}_g$ the power per volume unit absorbed by the MAL, and assuming that it is constant throughout the layer volume, we obtain:

$$\dot{q}_g \cdot A \cdot d_i + A \cdot \left[\frac{T_{i-1} - T_i}{\frac{d_{i-1}}{2 \cdot k_{i-1}} + \frac{d_i}{2 \cdot k_i}} \right] - A \cdot \left[\frac{T_i - T_{i+1}}{\frac{d_i}{2 \cdot k_i} + \frac{d_{i+1}}{2 \cdot k_{i+1}}} \right] = m_i \cdot c_{p_i} \cdot \frac{dT_i}{dt}. \quad (\text{M.2})$$

For the inner layer, layer 1, there is heat convection loss to the interior air, besides heat conduction loss to the adjacent layer. Considering the interior air almost still, the heat convection coefficient can be approximated by a low value, h_a , and the heat balance becomes:

$$A \cdot \left[\frac{T_2 - T_1}{\frac{d_2}{2 \cdot k_2} + \frac{d_1}{2 \cdot k_1}} \right] - A \cdot h_a \cdot (T_1 - T_a) = m_1 \cdot c_{p1} \cdot \frac{dT_1}{dt}, \quad (\text{M.3})$$

where T_a is the interior air temperature. To obtain this temperature, a heat balance on the interior air is performed:

$$A \cdot h_a \cdot (T_1 - T_a) = m_a \cdot c_{pa} \cdot \frac{dT_a}{dt}. \quad (\text{M.4})$$

For the outer layer, layer n , the blade surface in contact with the exterior airflow, there is heat conduction to the adjacent layer and heat convection loss to the exterior air. Heat balance is expressed by:

$$A \cdot \left[\frac{T_{n-1} - T_n}{\frac{d_{n-1}}{2 \cdot k_{n-1}} + \frac{d_n}{2 \cdot k_n}} \right] - A \cdot h_{\text{ext}} \cdot (T_n - T_\infty) = m_n \cdot c_{pn} \cdot \frac{dT_n}{dt}, \quad (\text{M.5})$$

where h_{ext} represents the exterior convection coefficient, which can be taken from the steady-state model for specific exterior conditions. It is considered constant along the specified surface area, A .

To calculate the above differential equations in EES, it will be needed to integrate $\frac{dT_i}{dt}$ to find the temperatures as a function of time. The numerical integration is performed through time steps between the initial time and the final simulation time. For a temperature T_i at time t , its value will be determined by:

$$T_i = \int_0^t \left(\frac{dT_i}{dt} \right) dt + T_{\text{initial}}, \quad (\text{M.6})$$

where T_{initial} is the initial temperature of layer i .

Simulation setup

To calculate the temperatures of each layer, the properties of each material need to be defined. This will not be detailed in this appendix, as the values introduced will depend on the blade materials and on the absorber material. When the results of this model are analysed, the properties used will be detailed, as well as the layer thicknesses, the initial conditions, and the atmospheric conditions.

The equations described in the mathematical formulation above were introduced in EES, and the setup is shown in Figure M.1. In this case, there were considered nine layers, and the MAL corresponds to the layer 5.

Figure M.2 shows an example of the results that can be obtained after integration, by specifying the complete model parameters. Only the first seconds of simulation are shown.

Formatted Equations

Balance on interior air

$$A \cdot h_a \cdot (T_1 - T_a) = m_a \cdot c_{p_a} \cdot dT_a dt$$

$$T_a = \int_0^{t_{\text{total}}} (dT_a dt) \cdot dt + T_{\text{initial}}$$

Heat balance on blade layers

step = 0.01 [s]

$$A \cdot \left[\frac{T_2 - T_1}{\frac{d_2}{2 \cdot k_2} + \frac{d_1}{2 \cdot k_1}} \right] - A \cdot h_a \cdot (T_1 - T_a) = m_1 \cdot c_{p_1} \cdot dT_1 dt$$

$$T_1 = \int_0^{t_{\text{total}}} (dT_1 dt) \cdot dt + T_{\text{initial}}$$

$$A \cdot \left[\frac{T_1 - T_2}{\frac{d_1}{2 \cdot k_1} + \frac{d_2}{2 \cdot k_2}} \right] - A \cdot \left[\frac{T_2 - T_3}{\frac{d_2}{2 \cdot k_2} + \frac{d_3}{2 \cdot k_3}} \right] = m_2 \cdot c_{p_2} \cdot dT_2 dt$$

$$T_2 = \int_0^{t_{\text{total}}} (dT_2 dt) \cdot dt + T_{\text{initial}}$$

$$A \cdot \left[\frac{T_2 - T_3}{\frac{d_2}{2 \cdot k_2} + \frac{d_3}{2 \cdot k_3}} \right] - A \cdot \left[\frac{T_3 - T_4}{\frac{d_3}{2 \cdot k_3} + \frac{d_4}{2 \cdot k_4}} \right] = m_3 \cdot c_{p_3} \cdot dT_3 dt$$

$$T_3 = \int_0^{t_{\text{total}}} (dT_3 dt) \cdot dt + T_{\text{initial}}$$

$$A \cdot \left[\frac{T_3 - T_4}{\frac{d_3}{2 \cdot k_3} + \frac{d_4}{2 \cdot k_4}} \right] - A \cdot \left[\frac{T_4 - T_5}{\frac{d_4}{2 \cdot k_4} + \frac{d_5}{2 \cdot k_5}} \right] = m_4 \cdot c_{p_4} \cdot dT_4 dt$$

$$T_4 = \int_0^{t_{\text{total}}} (dT_4 dt) \cdot dt + T_{\text{initial}}$$

Formatted Equations

$$\dot{q}_g \cdot A \cdot d_g - A \cdot \left[\frac{T_5 - T_4}{\frac{d_5}{2 \cdot k_5} + \frac{d_4}{2 \cdot k_4}} \right] - A \cdot \left[\frac{T_5 - T_6}{\frac{d_5}{2 \cdot k_5} + \frac{d_6}{2 \cdot k_6}} \right] = m_5 \cdot c_{p_5} \cdot dT_5 dt$$

$$T_5 = \int_0^{t_{\text{total}}} (dT_5 dt) \cdot dt + T_{\text{initial}}$$

$$A \cdot \left[\frac{T_5 - T_6}{\frac{d_5}{2 \cdot k_5} + \frac{d_6}{2 \cdot k_6}} \right] - A \cdot \left[\frac{T_6 - T_7}{\frac{d_6}{2 \cdot k_6} + \frac{d_7}{2 \cdot k_7}} \right] = m_6 \cdot c_{p_6} \cdot dT_6 dt$$

$$T_6 = \int_0^{t_{\text{total}}} (dT_6 dt) \cdot dt + T_{\text{initial}}$$

$$A \cdot \left[\frac{T_6 - T_7}{\frac{d_6}{2 \cdot k_6} + \frac{d_7}{2 \cdot k_7}} \right] - A \cdot \left[\frac{T_7 - T_8}{\frac{d_7}{2 \cdot k_7} + \frac{d_8}{2 \cdot k_8}} \right] = m_7 \cdot c_{p_7} \cdot dT_7 dt$$

$$T_7 = \int_0^{t_{\text{total}}} (dT_7 dt) \cdot dt + T_{\text{initial}}$$

$$A \cdot \left[\frac{T_7 - T_8}{\frac{d_7}{2 \cdot k_7} + \frac{d_8}{2 \cdot k_8}} \right] - A \cdot \left[\frac{T_8 - T_9}{\frac{d_8}{2 \cdot k_8} + \frac{d_9}{2 \cdot k_9}} \right] = m_8 \cdot c_{p_8} \cdot dT_8 dt$$

$$T_8 = \int_0^{t_{\text{total}}} (dT_8 dt) \cdot dt + T_{\text{initial}}$$

$$A \cdot \left[\frac{T_8 - T_9}{\frac{d_8}{2 \cdot k_8} + \frac{d_9}{2 \cdot k_9}} \right] - A \cdot (T_9 - T_{\text{ext}}) \cdot h_{\text{ext}} = m_9 \cdot c_{p_9} \cdot dT_9 dt$$

$$T_9 = \int_0^{t_{\text{total}}} (dT_9 dt) \cdot dt + T_{\text{initial}}$$

Figure M.1: Heat balances equations in EES transient model.

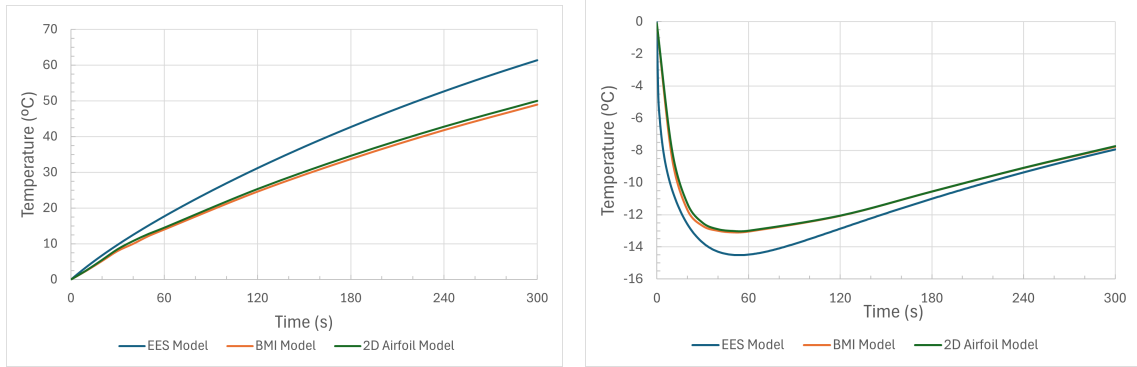
	1	2	3	4	5	6	7	8	9	10	11
	t [s]	T _a	T ₁ [C]	T ₂ [C]	T ₃ [C]	T ₄ [C]	T ₅ [C]	T ₆ [C]	T ₇	T ₈	T ₉
Row 1	0	1.000E-994	0	1.000E-994	1.000E-994	1.000E-994	0	1.000E-994	1.000E-994	1.000E-994	0
Row 2	1	1.016E-09	1.060E-09	7.268E-09	0.00003039	0.007505	0.3709	-0.2204	-0.8891	-1.266	-4.446
Row 3	2	8.626E-09	8.950E-09	5.493E-08	0.0000185	0.0296	0.7376	-0.9743	-2.269	-2.742	-6.166
Row 4	3	4.747E-08	4.881E-08	2.368E-07	0.00005975	0.06537	1.099	-1.929	-3.372	-3.862	-7.28
Row 5	4	1.713E-07	1.750E-07	6.907E-07	0.0001385	0.1139	1.454	-2.882	-4.343	-4.823	-8.127
Row 6	5	4.664E-07	4.744E-07	0.00000159	0.0002657	0.1745	1.804	-3.777	-5.216	-5.68	-8.839
Row 7	6	0.000001052	0.000001067	0.00000314	0.0004516	0.2462	2.148	-4.601	-6.007	-6.453	-9.467
Row 8	7	0.000002077	0.000002102	0.000005571	0.0007058	0.3284	2.488	-5.352	-6.724	-7.153	-10.03
Row 9	8	0.000003724	0.000003763	0.00000914	0.001037	0.4205	2.823	-6.035	-7.375	-7.788	-10.54
Row 10	9	0.000006199	0.000006256	0.00001413	0.001454	0.5217	3.153	-6.654	-7.965	-8.363	-11
Row 11	10	0.000009737	0.000009817	0.00002084	0.001964	0.6314	3.48	-7.215	-8.5	-8.885	-11.42
Row 12	11	0.0000146	0.0000147	0.00002958	0.002574	0.7492	3.803	-7.721	-9.884	-9.358	-11.8
Row 13	12	0.00002106	0.0000212	0.0000407	0.003291	0.8745	4.122	-8.179	-9.422	-9.785	-12.14
Row 14	13	0.00002942	0.00002961	0.00005456	0.004122	1.007	4.438	-8.591	-9.817	-10.17	-12.45
Row 15	14	0.00004002	0.00004024	0.00007152	0.005072	1.146	4.751	-8.962	-10.17	-10.52	-12.74
Row 16	15	0.00005317	0.00005345	0.00009197	0.006147	1.291	5.061	-9.296	-10.49	-10.83	-12.99
Row 17	16	0.00006924	0.00006958	0.0001163	0.007351	1.441	5.368	-9.594	-10.78	-11.11	-13.21
Row 18	17	0.00008861	0.00008902	0.0001449	0.00869	1.598	5.672	-9.861	-11.04	-11.37	-13.42
Row 19	18	0.0001117	0.0001121	0.0001783	0.01017	1.759	5.974	-10.1	-11.27	-11.59	-13.6

Figure M.2: Example of results obtained for each layer temperature after integration.

Appendix N

Comparison of Temperatures Variations With Time for EES Transient Model and COMSOL Models

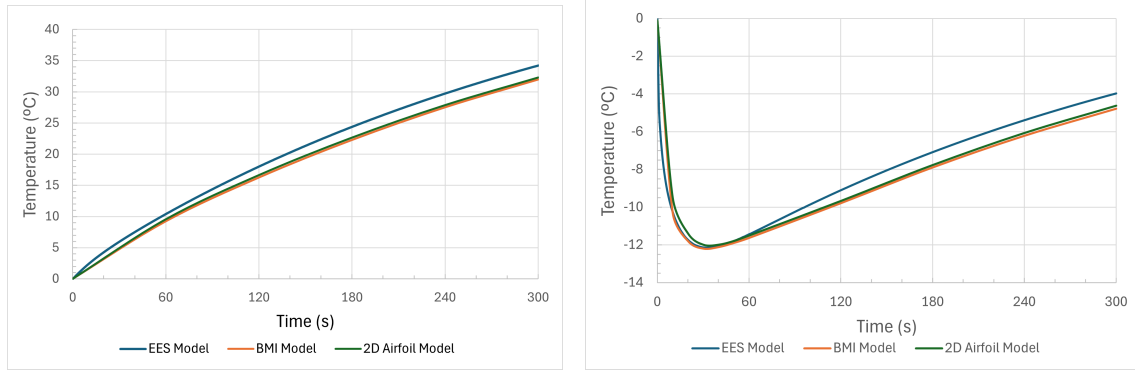
Figures N.1, N.2, and N.3 show the temperature variation throughout the simulation time, 300 seconds, comparing the results of the EES Transient Model with the BMI Model and the 2D Airfoil Model with constant convection coefficient (h_{ext}), for the three MAL materials: MWCNT-PP, CCFRP, and Eccosorb BSR-1, respectively.



(a) Variation of the MAL average temperature with time.

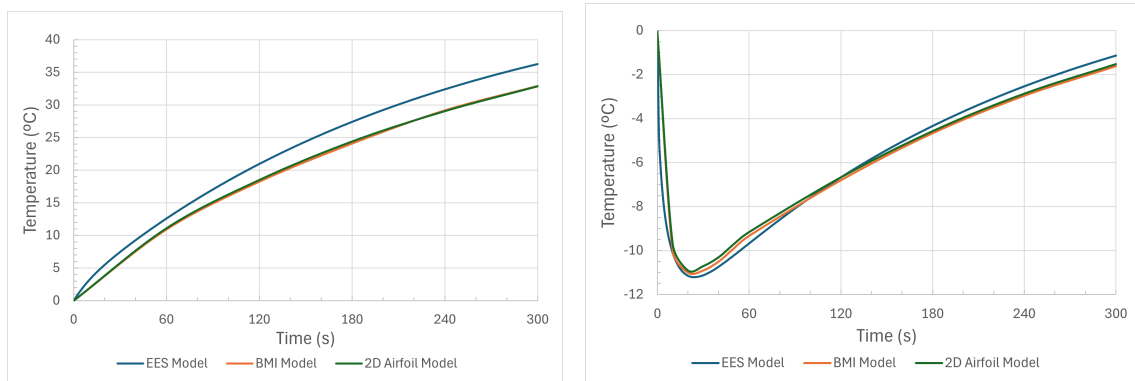
(b) Variation of the blade surface average temperature with time.

Figure N.1: Temperature variation with time for EES Transient, BMI, and 2D with constant h_{ext} Models, using MWCNT-PP in the MAL.



(a) Variation of the MAL average temperature with time. (b) Variation of the blade surface average temperature with time.

Figure N.2: Temperature variation with time for EES Transient, BMI, and 2D with constant h_{ext} Models, using CCFRP in the MAL.



(a) Variation of the MAL average temperature with time. (b) Variation of the blade surface average temperature with time.

Figure N.3: Temperature variation with time for EES Transient, BMI, and 2D with constant h_{ext} Models, using Eccosorb BSR-1 in the MAL.

Appendix O

Maximum Spacing Between Microwave Sources - MAL Model Simulations

This appendix includes the COMSOL simulations, for the MAL Model, performed to study the maximum spacing between microwave sources inside a wind turbine blade (Section [6.2.2](#)).

Figure [O.1](#) shows the power loss distribution inside the MAL for three different flat plate lengths: 0.2 m, 0.5 m, and 1 m. It is visible that flat plates with lengths greater than 0.5 meters do not achieve microwave energy absorption along their entire length.

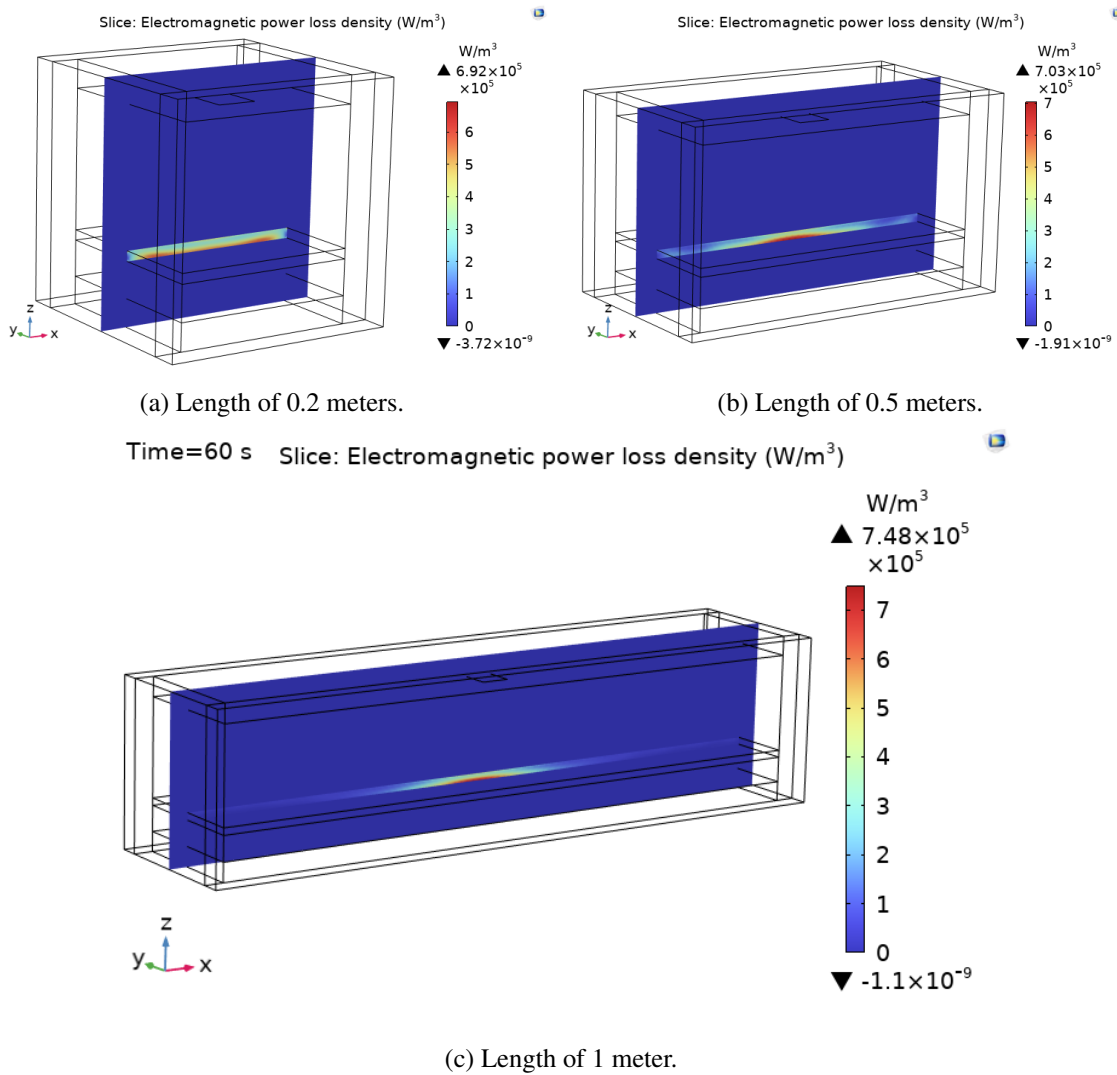


Figure O.1: Electromagnetic power loss distribution in the absorber, for the MAL Model, using three flat plate lengths.

Appendix P

Process and Calculations to Obtain the Power of the Microwave System

The heating power required near the tip of the blade is significantly higher than near the root, primarily due to the increased relative wind velocities at the tip. To evaluate the power requirements of the microwave anti-icing system in a simplified manner, the region of the blade affected by the MAL was divided into five sections (A, B, C, D, and E), as illustrated in Figure P.1. Each section was assigned specific external airflow conditions. The blade length considered is 70 meters, with the MAL integrated along two-thirds of the blade, starting from the tip, as the regions near the blade root are less susceptible to ice accretion. Dividing the two-thirds of the blade length into five sections results in a section length of 9.33 meters.

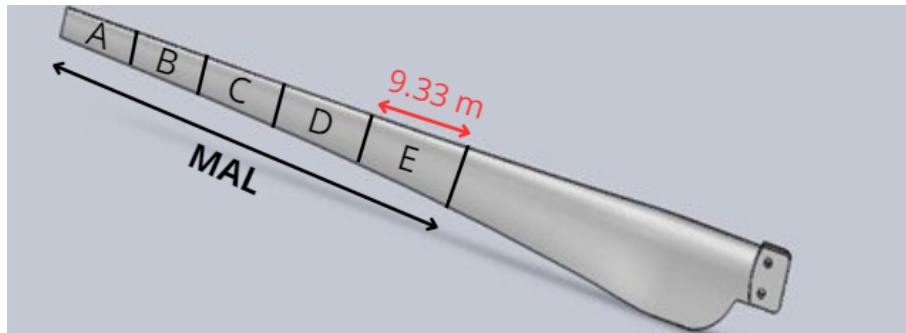


Figure P.1: 3D blade representation with the five regions considered for the power analysis, with the respective length.

The critical conditions assumed for this analysis were an ambient temperature of -20°C , a blade rotational speed of 8 RPM, and a wind upstream velocity of 20 m/s. With this values, the critical conditions for each of the five regions can be determined, with the wind relative velocity varying for each section, expressed by:

$$V_r = \sqrt{V_o^2 + V_{tan}^2}, \quad (\text{P.1})$$

where V_r is the relative wind velocity, V_o is the velocity of the wind upstream of the wind turbine, and V_{tan} is the tangential velocity of the blade.

The tangential velocity of the blade (V_{tan}) varies with the blade radial length (r), as expressed by the following equation:

$$V_{tan} = r \times \omega_r, \quad (P.2)$$

where ω_r is the rotational speed of the blade in rad/s. Since the rotational speed is 8 RPM, multiplying by the factor $\frac{2\pi}{60}$, we obtain 0.838 rad/s.

Using equation P.2, it is possible to obtain the tangential blade velocity for the five different regions, considering an average value for each region. Using equation P.1, the average relative wind velocity can be calculated for each region.

The power required to keep the blade surface steady-state temperature at least at 5°C, as a function of wind relative velocity, has been estimated using the EES Steady-state Model and is shown in Figure 4.5. This estimation was calculated for the leading edge, as this is the critical region of any cross-section of the wind turbine blade, regarding heating power requirement. Using these results for each respective relative wind velocity, the power requirement for each blade region was obtained.

To calculate the power per source, the value of 90 magnetrons per blade, as defined in Section 6.2.2, is used. Dividing the total number of magnetrons by the number of regions results in 18 magnetrons per section. By combining the number of magnetrons per section with the power requirement per surface area, the power that each source needs to absorb can be determined. Finally, using the power absorption efficiency of the selected absorber (3 mm of Eccosorb BSR-1) the supply power required per source is calculated.

The respective value of average relative wind velocity, power requirement per area, and power per source, for each region with critical conditions, is shown in Table P.1.

Table P.1: Wind relative velocity and power required to achieve a 5 °C surface temperature, for each section

Region	V_r	Power required (W/m ²)	Power per source (W)
A	58.3	5473	2261
B	51.0	5121	2115
C	44.0	4753	1963
D	37.2	4371	1806
E	30.9	3987	1647

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