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No-load Power Loss of a Rear Axle Gear Transmission: Measurement and Modelling

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Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.

Marie Curie

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Abstract

The fuel efficiency is becoming a increasingly important aspect when choosing a vehicle, due to the pollution, running costs and scarcity of fossil fuels. Besides, the generated heat due to energy losses will increase the operating temperature of mechanical components, leading to a lower life time. Therefore, there is a necessity of increase the vehicles efficiency, that can only be achieved by understanding the *phenomena* that are happening, as well as their influences.

In this work, it was given special attention to the rear axle, as one part of the vehicle drivetrain, that is responsible for power transmission between the gearbox and the wheels. Therefore it has also an important role in the vehicle efficiency. The major propose of this work was to study the contributions of all the different no-load losses in the rear axle, as well as analyse the influence of rotational speed and oil temperature. The results were obtained with no-load experimental tests, that were performed in a BMW 318d E46 differential, using Total Transmission Dual 9 FE 75W-90 oil, for different rotational speeds and oil temperatures.

Due to the many mechanical components of the differential, the losses can be divided in three major losses, rolling bearings, gears churning and seals losses. Several power loss models that exist in the literature for each power loss source were presented, in order to be possible perform a comparative analysis with the experimental results.

During the experimental work, it was not possible to measure all the different power losses separately that exist in a differential. The pinion rolling bearings, churning and seal losses and the crown wheel churning and rolling bearings allowed to conclude that almost every churning model could not be validated, except the Fossier [1] model that presented the best estimation of the power loss. For the rolling bearings, it was only possible to verify that none of the presented models have the same tendency of torque loss with the rotational speed, as the experimental tests showed that the torque loss tends to a constant value with the increase of speed.

From this study, it was also possible to conclude that the contribution of the crown wheel is in average 31 % of the total no-load power loss, while the majority of the no-load power loss was due to the pinion-shaft assembly, that included pre-loaded tapered roller bearings.

Due to the lack of models in the literature to properly calculate the power loss of the pre-loaded tapered rolling bearings (the pre-load is unkown), a parametric study was done and a model was developed. This model presents a good correlation with the experimental results, with a coefficient of determination of 0.97.

Resumo

Atualmente a eficiência energética está à tornar-se um aspeto importante na escolha de um automóvel, devido a poluição, escassez de combustíveis fósseis e aquecimento global. Além disso, o calor gerado pelas perdas vai aumentar a temperatura de funcionamento dos componentes mecânicos, diminuindo o seu tempo de vida. Portanto existe a necessidade de aumentar a eficiência, que só pode ser alcançado, se os fenómenos envolvidos forem conhecidos.

Nesta dissertação, foi dada especial atenção ao eixo traseiro, como um dos componentes da transmissão de um veículo responsável pela transmissão de potência entre a caixa de velocidades e as rodas. Portanto este elemento tem um papel importante na eficiência energética. O principal objetivo deste trabalho foi estudar a contribuição das diferentes perdas em vazio no eixo traseiro, assim como analisar a influência da velocidade de rotação e temperatura do óleo. Os resultados foram obtidos com testes experimentais em vazio, que foram realizados num diferencial de um BMW 318d E46, usando o óleo Total Transmission Dual 9 FE 75W-90, para diferentes velocidades de rotação e temperaturas do óleo.

Devido aos diferentes componentes do diferencial, as perdas de potência podem ser separadas em três grupos, rolamentos, chapinagem e vedantes. Alguns modelos de perdas de potência que existem na literatura, foram apresentados, onde foi possível realizar uma análise comparativa com os resultados experimentais.

Durante os testes experimentais, não foi possível medir as diferentes perdas de potência separadamente. As perdas dos rolamentos, de chapinagem e vedantes do pinhão e as perdas dos rolamentos e chapinagem da roda de coroa permitiram concluir que praticamente todos os modelos de chapinagem não representam a mesma tendência, exceto o modelo de Fossier [1], que apresenta a melhor previsão das perdas de potência. Em relação aos rolamentos, só foi possível verificar que nenhum dos modelos apresentados representa a mesma tendência das perdas de binário com o aumento da velocidade de rotação, como os testes mostram que esta tende para um valor constante com o aumento da velocidade.

A partir deste estudo, também foi possível concluir que as perdas de potência da roda de coroa apenas representam 31 % das perdas totais em vazio no diferencial, valor que pode ser explicado pela elevada contribuição das perdas do conjunto veio-pinhão que está montado em rolamentos de rolos cónicos pre-carregados.

Uma vez que não existem modelos que convenientemente estimem as perdas de potência de rolamentos de rolos cónicos pré-carregados (a pré-carga neste caso era desconhecida), foi feito um estudo paramétrico e desenvolvido um modelo para o efeito. Este modelo apresenta uma boa aproximação com os resultados experimentais, com um coeficiente de determinação de 0.97.

Keywords

No-load power loss

Torque loss

Churning losses

Rear Axle

Differential

Tapered roller bearings

Hypoid gears

Seals

Starting Torque

Palavras-Chave

Perdas de potência sem carga

Perdas de binário

Perdas por chapinagem

Eixo traseiro

Diferencial

Rolamentos cónicos

Engrenagens hipóides

Vedantes

Binário de arranque

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Nomenclature

Symbol	Description	Units
α	Pressure angle	rad
α_{lub}	Thermal expansion coefficient	-
β	Helix angle	rad
β_s	Seal and bearing type constant	-
β_{lub}	Thermoviscosity coefficient	-
$\Delta\theta$	Lubricant temperature variation	-
η	Dynamic viscosity of the lubricant	N s m^{-2}
γ	Centrifugal acceleration	m s^{-2}
μ	Constant that depends on the movement of rolling bearing	-
μ^{seal}	Seal friction coefficient	-
μ_1	Friction coefficient dependent on load and bearing design	-
μ_{EHL}	Sliding friction coefficient in full-film conditions of rolling bearing	-
μ_{sl}	Sliding friction coefficient	-
ω	Angular speed	rad s^{-1}
ϕ_{bl}	Weighting factor for the sliding friction coefficient of rolling bearing	-
ϕ_{ish}	Intlet shear heating reduction factor	-
ϕ_{rs}	Kinematic replenishment/starvation reduction factor	-
ρ	Lubricant density	kg m^{-3}
ρ^p	Lubricant density at the required pressure	kg m^{-3}
ρ^T	Lubricant density at the required temperature T	kg m^{-3}
ρ_0^p	Lubricant density at atmospheric pressure	kg m^{-3}
ρ_0^T	Lubricant density at the reference temperature T_0	kg m^{-3}
θ	Angle of the oil level in the gears	rad
a	Distance between gear centre and oil level	-

a_{lub}	Lubricant constant	$mm^2\ s^{-1}$
b	Gear face width	m
b_{lub}	Lubricant constant	-
c	Gear oil width	-
C_m	Dimensionless drag torque	-
C_{ch}	Churning torque	N·m
C_{exp}	Crown wheel experimental results	N·mm
C_{FS}	Crown wheel churning loss according to Fossier	N·mm
c_{lub}	Lubricant constant	-
C_{Sp}	Splash oil factor	-
D	Bearing outside diameter	mm
d	Rolling bearing	mm
d_m	Bearing mean diameter	mm
d_p	Gear pitch diameter	m
d_s	Seal conterface diameter	mm
d_{sh}	Shaft diameter	mm
F	Resulting bearing load	N
f_0	Coefficient taking into account bearing design and lubrication method	-
f_1	Coefficient taking into account direction of load application	-
F_a	Axial load at rolling bearing	N
F_D	Coefficient that expresses the effect of temperature over the viscosity	W
F_r	Radial load at rolling bearing	N
F_R^s	Seal radial force	N
Fr	Froude number	-
g	Gravitational acceleration.	$m\ s^{-2}$
G_{rr}	Geometric and load dependent variable for rolling	-
G_{sl}	Geometric and load dependent variable for sliding	-
h	Oil immersion depth	m

$H_{housing}$	Housing height	m
H_{tooth}	Tooth height	m
$i_{finaldrive}$	Differential gear ratio	-
k	Assembly rigidity factor	k
K_{lub}	Lubricant constant	-
K_{oil}	Oil temperature	K
K_{S1}	Seal and bearing type constant	-
K_{S2}	Seal and bearing type constant	-
L_{arc}	Arc length	m
$L_{housing}$	Housing width	m
M	Total friction moment of rolling bearings	N·mm
m	Gear module	m
M_0	Rolling bearing no-load dependent torque loss	N·mm
M_1	Rolling bearing load dependent torque loss	N·mm
M_{drag}	Frictional moment from drag losses, churning, splashing, etc. in an oil bath	N·mm
m_{lub}	Lubricant constant	-
M_{rr}	Rolling fictional moment of rolling bearings	N·mm
M_{seal}	Frictional moment from integral seals of rolling bearings	N·mm
M_{sl}	Sliding frictional moment of rolling bearings	N·mm
n	Rotational speed	rpm
n_{lub}	Lubricant constant	-
p	Required pressure	GPa
P_V	Total power loss	W
P_{exp}	Pinion experimental results	N·mm
P_{FS}	Pinion churning loss according to Fossier	N·mm
P_{VD}	Seals power loss	W
P_{VL0}	Rolling bearings no-load power loss	W

P_{VLP}	Rolling bearings load power loss	W
P_{VL}	Rolling bearings total power loss	W
P_{VX}	Auxiliary power loss	W
P_{VZ0}	Gears no-load power loss	W
P_{VZP}	Gears load power loss	W
Q	Volumetric flow rate of oil	ml s^{-1}
r_o	Gear outer radius	m
r_p	Gear pitch radius	m
R_{tire}	Vehicle tire radius	m
RB_c	Crown wheel rolling bearings torque loss	N·mm
RB_p^{exp}	Pinion rolling bearings experimental loss	N·mm
Re	Reynolds number	-
Re_c	Critical Reynolds number	-
S_m	Gear submerged area	m^2
$S_{1;2}$	Sliding frictional moment of the rolling bearing	N·mm
T	Oil temperature	°C
T_{bath}	Oil bath temperature	°C
T_{des}	Desired oil temperature at the rolling bearings	°C
T_{exp}	Total torque loss without the output shaft seals	N·mm
T_{oil}	Oil temperature	°C
T_{VL}	Rolling bearings oil temperature	°C
u	Speed ratio	-
v	Kinematic oil viscosity	mm^2 s^{-1}
$V.I.$	Viscosity Index	-
V_0	Oil volume	m^3
v_1	Kinematic viscosity at the temperature θ_1	-
v_2	Kinematic viscosity at the temperature θ_2	-
V_p	Gear submerged volume	m^3

v_{40}	Kinematic viscosity at 40 °C	$mm^2\ s^{-1}$
V_{lin}	Vehicle linear speed	$m\ s^{-1}$
V_{sim}	Pinion seal loss	N·mm
v_{t0}	Reference velocity	$m\ s^{-1}$
v_t	Pitch line velocity	$m\ s^{-1}$
W_{pinion}	Angular velocity of the differential pinion	$rad\ s^{-1}$
W_{wheel}	Angular velocity of the wheel	$rad\ s^{-1}$
Y	Axial load factor	-
Z	Number of teeth	-

1 Introduction

In our days, the fuel efficiency of vehicles is a very important aspect to consider, because of the scarcity of fossil fuels, the increase in pollution and the global warming [2]. In addition the heat generated and the increase of the temperature due to excessive power losses within the mechanical components adversely impact gear and rolling bearing contact fatigue and scuffing failure modes [3]. Therefore there is a necessity to reduce the power losses in vehicles, reducing the emissions and heat generated.

The vehicle transmission is constituted by several moving parts, like rolling bearings, gears, seals, and so on. Each one of these, represents a small loss that summed up, according to California Energy Commission, represent 5.6% of the total energy given to the engine. This only happens because of the friction and sliding between the different components and the churning losses. The Figure 1.1 represents the paths of energy through a typical gas-powered vehicle in city driving.

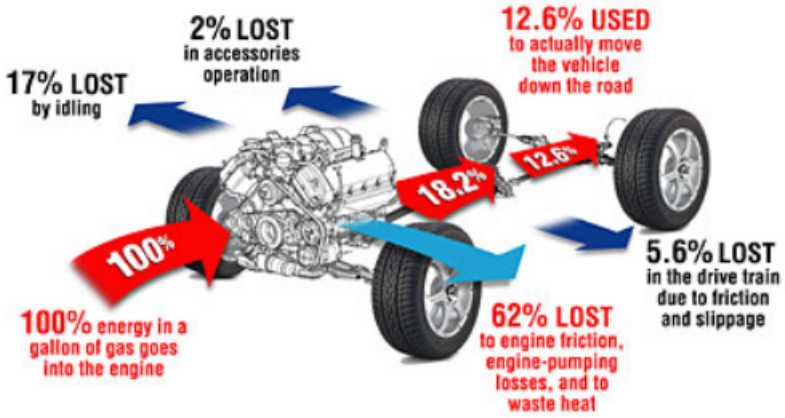


Figure 1.1: Energy efficiency of a vehicle [4].

Seeing that the vehicle transmission has a significant impact on the overall efficiency, there is the necessity of understanding what is happening. The differential is one of the components of the transmission, as it will be better explained in the next chapter. So, in this dissertation, the main objective is to experimentally evaluate the no-load losses in a vehicle rear axle in an incremental and progressive way in order to understand the influence of each of the components in the no-load losses. After this steps are complete a better understanding and modeling of the no-load loss in the rear axle is possible.

The power losses in a differential can be divided in two groups:

- No-load losses - represent the losses that depend essentially on the rotational

speed of the system, here the oil churning and windage, the viscous dissipation in the rolling bearings and friction of the seals can be included. The churning losses are due to the contact between the partially submerged moving surfaces, in this case the gears and the lubricant. The windage losses, as the churning losses, are due to the contact between moving surfaces, the gears and the air, that in this case can be disregarded, because of it's low influence in the losses.

- Load losses - represent the losses that depend essentially on the load that is applied to the system, here are included the friction between the surfaces of gears and the rolling bearings. This losses are due to the friction forces created during rolling and sliding inherent to this components.

When the rear axle rotates at a reasonably high speed, for example driving in a motorway, the major losses are the ones that depend essentially on the speed, in this case, the no-load. While load dependent losses, are more relevant, in the case of low speed and high loads, as driving in a city [3].

Furthermore, the lubricant has an important role in the efficiency of the transmission, because of it's intrinsic characteristic, the oil viscosity. So, this dissertation includes a chapter dedicated to lubricant properties and different standards. It is important to notice that no-load losses depend essentially on the viscosity and density, while load losses depend essentially on the viscosity and the different additives presented in the lubricant, that will guarantee specific characteristics.

1.1 Objectives and Scope

In this dissertation, the main objective is to separate all the different no-load power losses that exist in the differential, trying to overcome the problems that appeared to others who tried to perform similar works in the past [5, 6]. Another objective is to adapt the existing models to the experimental results, in order to be possible to estimate this type of power loss.

This can only be achieved with experimental tests, providing the necessary data to be possible to modulate the different power losses. Therefore in this dissertation, the several tests will be presented, where their results will be analysed to verify their coherence, always with the intention of obtaining all the different losses.

1.2 Thesis Outline

This dissertation is divided in 7 chapters, where all research, experimental tests and analyses are presented.

Chapter 1 - **Introduction** is reserved to do a brief presentation of the dissertation objectives, as well as the description of the work that will be carried on.

Chapter 2 - **Vehicle Drivetrain** is dedicated to present an introduction of the differential that is used and explanation of its main functions in a drivetrain.

Chapter 3 - **Rear Axle Lubrication** displays lubricant that will be used in the tests, as an explanation of its main properties and requirements for this specific operating conditions. This chapter also includes a brief explanation of the differential lubrication method, as well as another method that will be used during the experimental tests.

Chapter 4 - **Power Loss Models** reveals some power loss models that already exists in the literature, specifically for the differential losses contributors, where it is also possible to see a comparative analysis between them.

Chapter 5 - **Experimental Tests** presents all the experimental tests performed, where all the results are presented, as well as all the problems that were found and their solutions.

Chapter 6 - **Results Analysis** presents a full analysis to all the obtained results, where its also displayed a comparison with the previous presented models. This results lead to some conclusions.

Chapter 7 - **Conclusions and Future Works** is dedicated to do a brief presentation of all the conclusions that were taken during this dissertation. Some ideas/improvements are also presented in this chapter for future works.

2 Vehicle Drivetrain

The drivetrain of a vehicle is the group of components that deliver power of the engine to the wheels. This means that the drivetrain has the responsibility of transferring the mechanical energy and equalize the rotation between the engine and the wheels. In Figure 2.1, it is possible to see the different constituents of an AWD (All-wheel drive) drivetrain.

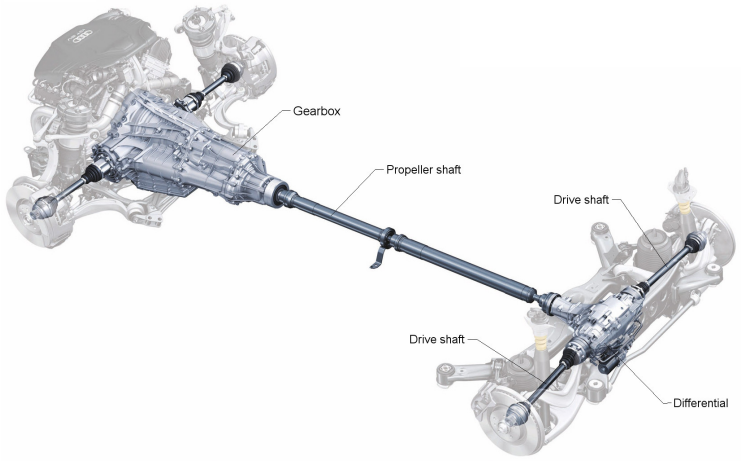


Figure 2.1: Drivetrain architecture (Audi A6 quattro) and main components [7].

Since the major losses of a drivetrain are present in the gearbox and the rear axle, because of the moving parts, including gears, rolling bearings and seals, in this dissertation special relevance to the losses in the differential will be given.

2.1 Differential Components

The differential is a geared mechanism responsible for transferring the movement from the gearbox to the axles, that is connected to the wheels. It is composed by a pair of hypoid gears, a planetary gear set, rolling bearings to support the shafts and seals to prevent oil leaks. In Figure 2.2, it is possible to visualise some of the components of a rear axle.

When a vehicle is driving in a straight line, both wheels turn at the same speed. But if the vehicle is turning a corner, one wheel will turn faster than the other, as represented in Figure 2.3. This means that the differential has to be capable of apply a final reduction, increasing the available torque and rotate the driving axles at different speeds, allowing the vehicle to corner. It is also responsible for change the power flow 90 degrees [8].

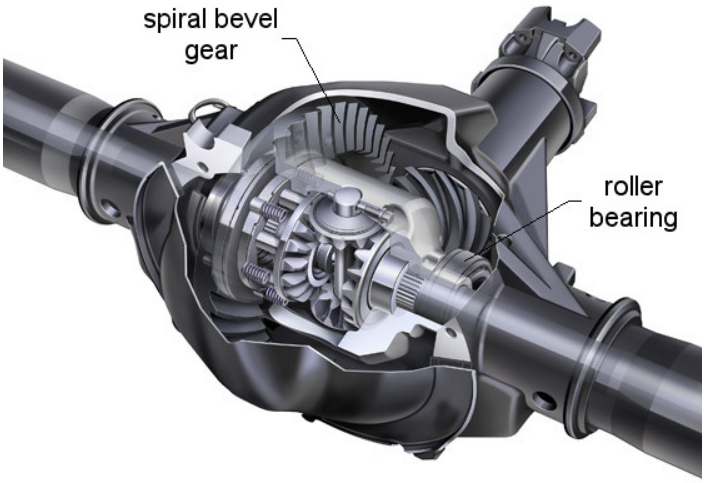


Figure 2.2: Rear axle components [9].

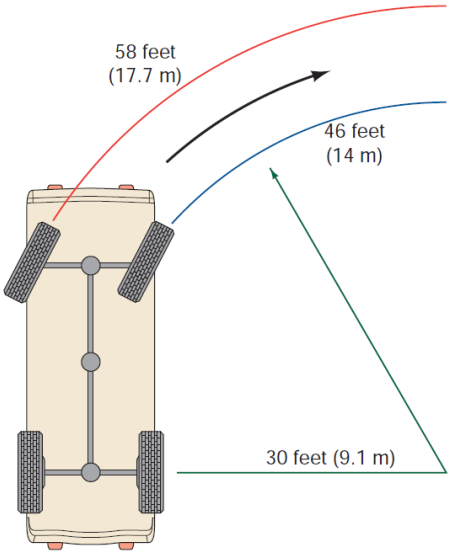


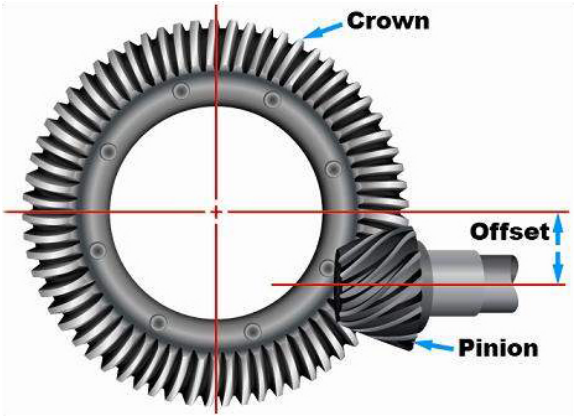
Figure 2.3: Travel of wheels when a vehicle is turning a corner [8].

2.1.1 Hypoid Gears

Usually, in a rear axle gearing is composed by hypoid gears. The main characteristic of this type of gears is that the axis of rotation do not have to intersect, in order to transfer power, unlike what happens with the bevel gears. This type of gears are mounted in a crossed shaft arrangement, where the pinion is deviated from the centre. In Figure 2.1.1, it is possible to visualise a hypoid gearing and the corresponding shafts offset. In addition to the fact that the axles do not have to intersect, another main characteristic is the fact that this gears form a elliptical area of contact, due to the hyperbolic shape of the teeth.



(a) Hypoid gear.



(b) Hypoid gear offset.

Figure 2.4: Hypoid gear [10].

The main advantages of hypoid gears, when compared to bevel gears are [10, 11, 12]:

- **Offset** - The offset between the input and output shafts allows to drop the transmission of a vehicle. This means that it is no longer necessary to have such a high tunnel to the transmission cross from the gearbox to the rear axle;
- **High Gear Ratios** - In an hypoid gearbox, the spiral angle of the pinion is larger than the spiral angle of the gear, so the pinion diameter can be larger when compared to a bevel gear. This allows higher gear ratios (up to 200:1);
- **Silent Gearing** - The high contact ratio and sliding direction allows for a silent gearing, without jolts neither vibrations;
- **Better Strength** - As explained before, the fact that the pinion diameter is larger, will provide better tooth resistance and the increased transmitted torque capabilities;
- **High Rigidity** - Because of the offset, in some specific gearboxes it is possible to cross the pinion shaft through the gearbox. This allows to use a second rolling bearing to support the pinion shaft.

The hypoid gearboxes also present some disadvantages, when compared to bevel gears [10, 11, 12]:

- **Precise Machining** - Due to the precise and complicated process of machining, only a few specialist manufacturers can make them, which can increase the production costs;
- **Rigid Assembly** - This type of gears require a rigid assembly, in order to maintain its position, when submitted to high load. The pinion shaft should be mounted in tapered roller bearings and with an high preload;
- **Sliding** - The sliding velocity in hypoid gears has an vertical component as verified in bevel gears, and also additional horizontal component. This means that it will have a higher sliding, therefore a lower resistance to wear. This problem can be overcome with the use of lubricants, that are specially designed for hypoid gears;
- **Running-in** - Due to the high slidding, hypoid gears require a good running-in, so they do not over heat, when submitted to severe work conditions;
- **Lubricant** - The hypoid gear lubricant has many additives to overcome the problems of extreme pressure, wear and friction, which will increase the costs of the lubricant and inhibit the use of copper base materials, as the additives will react with the copper;

- **Heating problems** - Due to the high sliding velocities, it is necessary to assure a good heat transfer to avoid overheating problems in the gears.

When using hypoid gears, it is important to fulfil the lubrication needs that are required. The sliding velocities could achieve velocities of 5 to 6 m s^{-1} in the primitive surface, for normal rotation speeds, while in this area for bevel gears, we do not have sliding. In the top of the gears teeth, this velocity can achieve values of 10 to 15 m s^{-1}. In addition, the gears are subjected to high pressure, between 1000 and 1500 MPa, which also demands the use of lubricants with extreme pressure additives [11].

2.1.2 Planetary Gear Set

The planetary gear set is composed by planets and suns gears, and is responsible to assure that the output shafts can rotate at different velocities, allowing the vehicle to properly corner. In Figure 2.5 and 2.6, it is possible to visualize the planetary gear set.

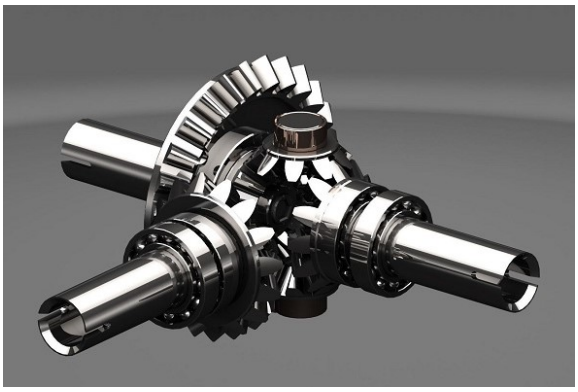


Figure 2.5: Planetary gear set [13].

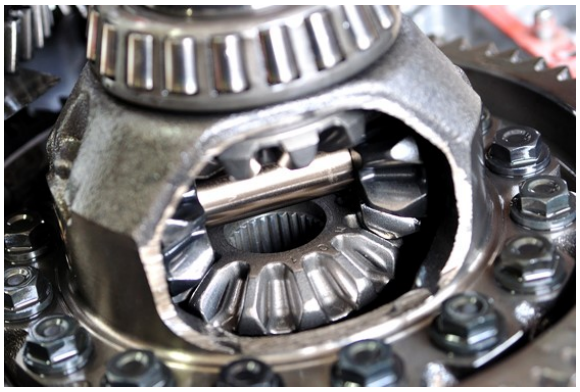


Figure 2.6: Differential gear set [14].

2.1.3 Tapered roller Bearings

As explained before, the hypoid rear axle gear requires a rigid assembly, that can only be assured by tapered roller bearings with preload. This type of rolling bearings can support both axial and radial loads, provide very narrow geometrical tolerances and high preload capability, assuring a constant and accurate gear mesh [15]. One main disadvantage of this type of rolling bearings is the high friction losses, especially when a high preload is applied.

As observed in Figure 2.7, usually there are 4 tapered roller bearings. The ones that support the pinion shaft, require a high preload to assure a rigid assembly, therefore one of the main power loss of the differential.

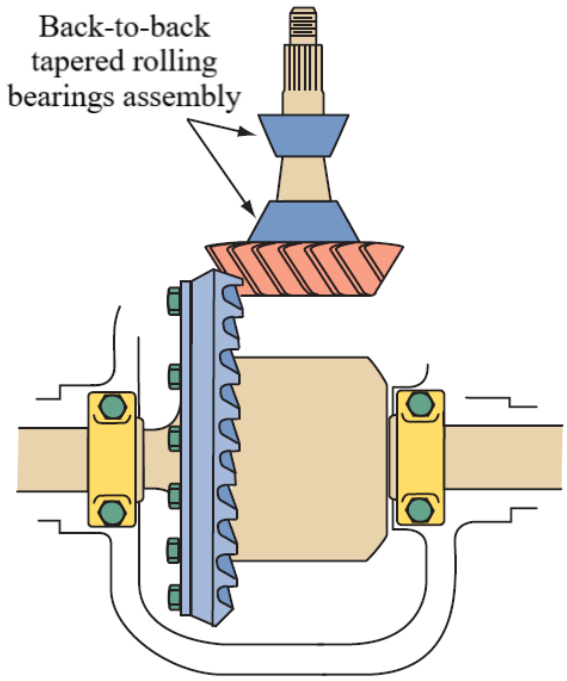


Figure 2.7: Pinion supported by tapered roller bearings [8].

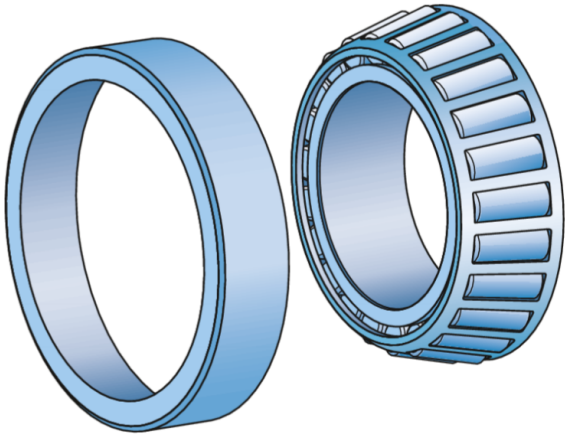


Figure 2.8: Tapered roller bearing [15].

2.1.4 Seals

The differential uses lubricant oil, therefore it is necessary to use seals to prevent any lubricant contamination by exterior dust and lubricant leak. Usually, this type of seals are made of PTFE (Polytetrafluoroethylene) with a dust lip of FKM (Viton), material that provide a low friction coefficient. In Figure 2.9, it is possible to observed on of the seals used in the differential.



Figure 2.9: Corteco seal [16].

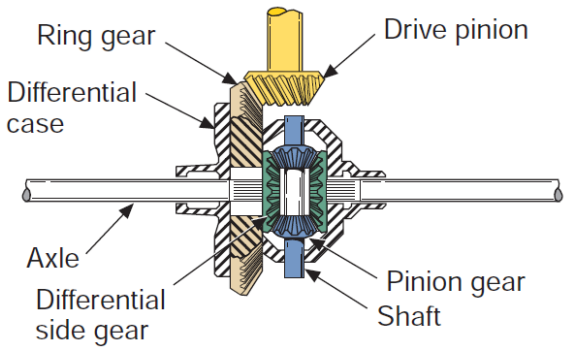
2.2 Types of Differentials

Depending on the working conditions that the rear axle will be operating, the differentials can be divided in 2 major types, open differentials and limited slip differentials. In this chapter, it will be discussed the main advantages of each one and it will be explained how they work.

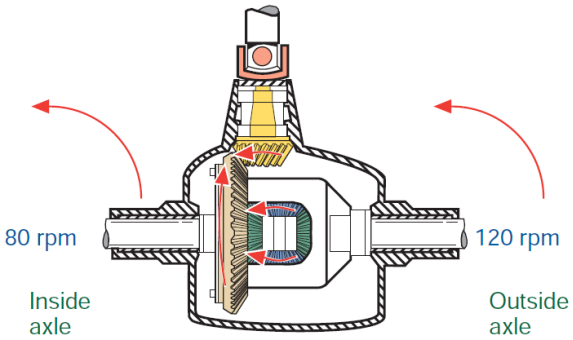
2.2.1 Open Differentials

Most of the differential are open differentials, which means that they assure the same torque transmitted and allow different speeds for both output shafts. This represents a big disadvantage, as the transmitted torque is always limited by the wheel with less traction. For example, if one of the driving wheels is on ice, as an open differential assures the same torque for both wheels, the transmitted torque will be practically none and the wheel on ice will be spining. This situation places stress on the differential gears, the amount of heat developed increases rapidly, the lubricating film breaks down and the parts are damaged.

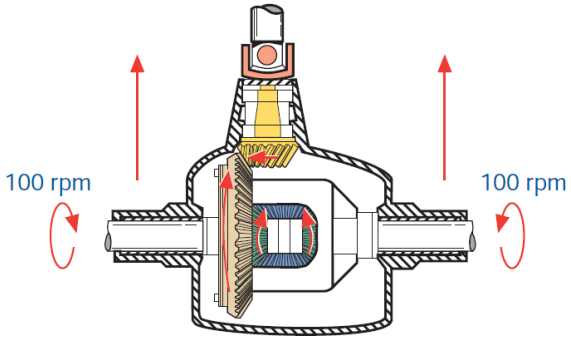
As it is possible to visualize in Figure 2.10, the set of planets and suns gears are responsible to compensate any speed differences between the output shafts. When the vehicle is turning left, as the pinion turn to allow the left-side gear to increase speed, a reverse action, known as a reverse walking effect, is produced on the right-side gear. It slows an amount that is inversely proportional to the increase on the left-side gear [8].



(a) Differential components.



(b) Differential action while turning left.

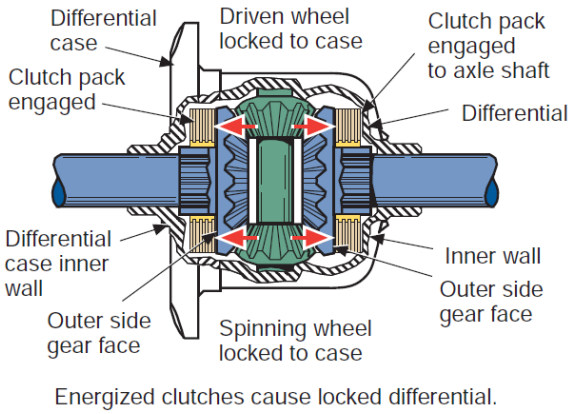


(c) Differential action while moving straight.

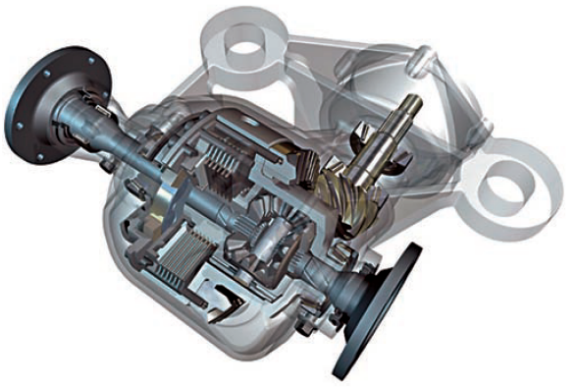
Figure 2.10: Open differential [8].

2.2.2 Limited Slip Differentials

Limited slip differentials (LSD) were designed to overcome the problem when slippery conditions are found. This type of differentials only allows a small amount of speed difference in both output axles, providing different amounts of torque in each wheels, when slippery conditions are found.



(a) Action of the clutches in a limited slip differential.



(b) Limited slip differential.

Figure 2.11: Limited slip differential with friction clutches [8].

Usually, this type of differentials use friction materials to transfer the torque applied to a slipping wheel to the one with traction, as represented in Figure 2.11. When one of the wheels loses traction, the clutches are activated, normally by 2 cone shaped parts, that will lock the side gears to the differential case. This will provided a locked differential, which will assure that the output shafts will rotate as the same speed and all the necessary torque to each wheel [8].

Limited slip differentials, can also be designed using a gear base, instead of a clutch, known as torsen differential. This units provide a quicker response to traction changes and do not lose their effectiveness with wear, although they use a more complex design [8].

2.3 Differential Under Study

In order to perform this experimental campaign, a differential from a BMW 318d E46 was used, Figure 2.12. This specific differential is an open differential and has the final reduction displayed in equation 2.1.

$$i_{red} = \frac{43}{14} \approx 3.07 \tag{2.1}$$



Figure 2.12: Differential without the back cover.

2.3.1 Differential Gears

As an open differential, this rear axle gear set is composed by hypoid gear pair, sun and planet gear set. In Table 2.1, some relevant parameters about the gears that were directly measured from the differential components are presented.

As this study is about moving in a straight line, both the sun and the planet gears will remain fixed.

Table 2.1: Geometrical parameters of the differential gears.

Parameter	Pinion	Crown Wheel	Sun Gear	Planet Gear
Number of Teeth	14	43	17	10
Outer Diameter / mm	93	184	79	54
Inner Diameter / mm	65	130	51	36
Pitch Diameter / mm	79	157	-	-
Module / mm	4	4	-	-
Width / mm	39	15	-	-

2.3.2 Differential Rolling Bearings

The differential has four tapered roller bearings, two in the pinion shaft and the other two are in the output shafts and are responsible for supporting the crown wheel. The used rolling bearing references and some of its dimensions are presented in the Table 2.2.

Table 2.2: Rolling bearings in the differential

Location:	Pinion	Input coupling	Output shaft
Actual Rolling Bearing	Koyo HM 801310	Koyo HM 88542	FAG F-801298-TR1P -H79-T29
Equivalent SKF Rolling Bearing	SKF HM 801346/310/Q	SKF HM 88542/510/Q	SKF 369 S/2/362 A/2/Q
Quantity	1	1	2
Bore Diameter / mm	38.1	31.75	47.625
Outside Diameter / mm	82.55	73.025	88.9
Width / mm	29.37	29.37	20.638

2.3.3 Differential Seals

In the differential, three seals are used, one in the input coupling and one in each output shaft. Some information regarding the seals is presented in Table 2.3.

Table 2.3: Seals used in the differential.

Location:	Input coupling	Output shaft
Actual Seal	Corteco 01027755B	Corteco 01033294B
Quantity	1	2
Shaft Diameter / mm	45	44
Housing Diameter / mm	75	90.1

It should be noticed that the manufacturer of seals used in the differential, Corteco, is one brand of Freudenberg, the manufacturer that presented the Simrit seal power loss model.

3 Rear Axle Lubrication

The main function of lubricants are the minimisation and control of friction between the solid surfaces in touch, making the relative movement easier.

The evolution of mechanical components has created new demands for lubrication. Therefore in addition to the decrease and control of friction, the lubricant has to be capable of minimizing surface wear, improve heat transfer, run at higher temperatures, remove wear particles from inside the contact, inhibit the corrosion and be miscible with other chemical substances, namely the additives that will improve its properties. Recently, the seeking to decrease the environmental impact has created new demands for the toxicity and biodegradability of the lubricant. The higher operational temperatures had led to higher oil oxidation of lubricants, consequently reducing the oil service time.

Nowadays, lubricants are made of a base fluid that can either be of synthetic or mineral origin. To this base fluid additives are added, in order to fulfil the requirements of the lubricant. The mineral oils are the most used oil base, because of its abundance in the nature and it is relatively cheap. The synthetic base oils were developed to solve specific difficult problems of lubrication.

A good lubricant should be sufficiently viscous to maintain a lubricant film, but in the other hand, it should have the lower viscosity possible to remove heat and lower the lost power of the viscous drag. The lubricant should also be stable under thermal pressures and oxidation, have low volatility and control the friction and wear [11].

3.1 Oil Physical Properties

The oil physical properties are mainly dependent of the base oil used and are the most important specification of the lubricant, when it is necessary to choose the appropriate lubricant for a specific lubrication needs.

In this chapter, it will be discussed some of the most important physical properties of the oils, that assure its qualities as a good lubricant.

3.1.1 Viscosity

One of main characteristic of lubricants is the viscosity, as it will determine the formation of a lubricant film. The increasing viscosity of the lubricating oil results in a thicker lubricant films, improving the antiwear, damping properties and scuffing load capacity [17].

Viscosity of a fluid is the quantity that describes a fluid's resistance to flow. Fluids resist the relative motion of immersed objects through them as well as to the motion of layers with differing velocities within them [18]. This resistance can be calculated using Newton's formula referring to laminar flow of a fluid between a moving surface with a velocity V and a fixed surface, as represented in Figure 3.1.

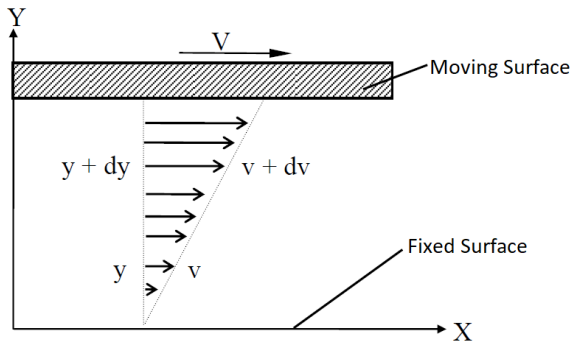


Figure 3.1: Laminar flow of a fluid [11].

Between the different "layers" of fluid will be moving at different velocities V, from 0 to V [11]. There are two ways of defining the viscosity. Dynamic viscosity μ, as explained before, take in consideration of the resistance of the fluid to flow and its S.I. units are mPa.s, which correspond to 1 centipoise (cPo). Kinematic viscosity v, is a measure of the resistance flow of a fluid under the influence of gravity and it is usually measured using a capillary viscometer. The units of the kinematic viscosity is $mm^2\ s^{-1}$, corresponding to 1 centistoke (cSt) [18].

Variation of viscosity with temperature

The temperature has the main influence on oil viscosity and for the most part of the lubricants, as the temperature increases the viscosity will decrease. In Figure 3.2, it is possible to visualize the viscosity of an ISO VG 32 oil with temperature.

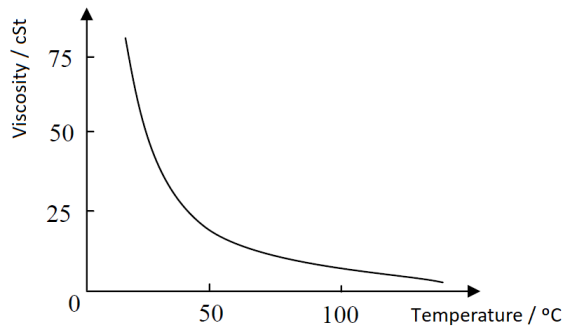


Figure 3.2: Viscosity variation with the temperature for a paraffinic mineral oil (Oil ISO VG 32) [11].

Viscosity Index

The viscosity index is a parameter that allows to compare the sensitivity to temperature on viscosity variation independently of the absolute viscosity value. With this information it is possible to obtain the oil viscosity index, using equation 3.1.

$$V.I. = \frac{L - U}{L - H} \cdot 100 \tag{3.1}$$

Were **L** and **H** are the reference oil viscosities at 40 °C and **U** is the viscosity of the oil that we want to calculate the viscosity index. This variables can be observed in Figure 3.3. After analysing this figure, it is also possible to conclude that the higher the viscosity index, the lower the variation of the viscosity with the temperature.

It should be noticed that the viscosity index it is not sufficient to characterize an oil. Two different oils with the same viscosity index, may not present the same variation of viscosity with temperature [11].

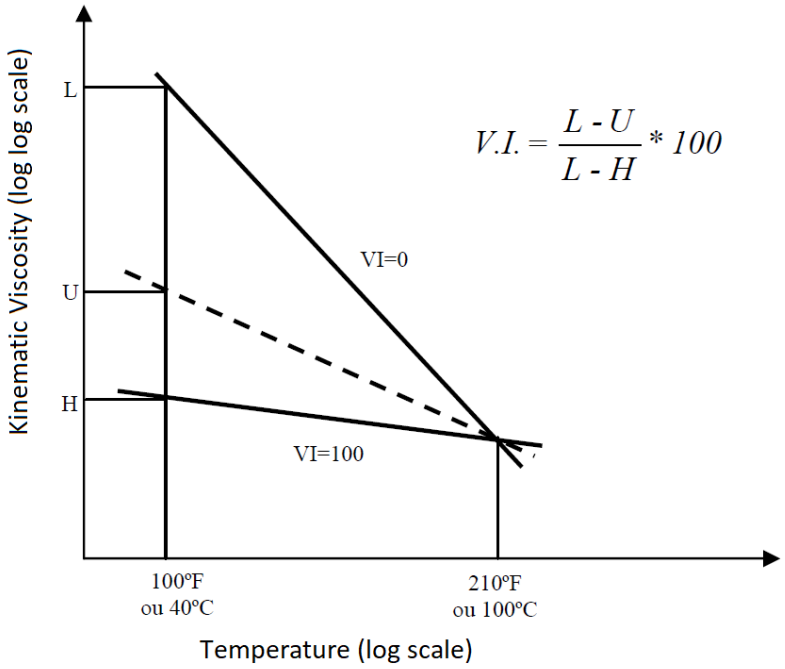


Figure 3.3: Definition of viscosity index [11].

Cameron

The necessity to represent the viscosity variation with the temperature, led to its modeling. Cameron proposed the simplest equation 3.2.

$$v_1 = v_0 \cdot e^{-\beta_{lub} \cdot \Delta\theta} \tag{3.2}$$

Where:

- v_1 - Kinematic viscosity at the temperature θ_1;
- v_0 - Kinematic viscosity at the temperature θ_0;
- β_{lub} - Thermoviscosity coefficient;
- $\Delta\theta$ - Lubricant temperature variation.

ASTM D341

The ASTM D341 has also proposed a formulation that represents the oil viscosity for a respective temperature. This formulation is presented in equation 3.3 and can be simplified in order to obtain the viscosity, as it is presented in equation 3.4.

$$\log\log(v + a_{lub}) = n_{lub} - m_{lub} \cdot \log(K_{oil}) \tag{3.3}$$

$$v = 10^{10^{n_{lub} - m_{lub} \cdot log(K_{oil})}} - a_{lub} \tag{3.4}$$

Where:

- v - Kinematics viscosity [$mm^2\ s^{-1}$];
- K_{oil} - Oil temperature [K];
- m_{lub}, n_{lub}, a_{lub} - Lubricant constants.

For mineral oils, the constant **a** assume the value of 0.7 $mm^2\ s^{-1}$.

Vogel

Vogel has developed a more exact expression to define the viscosity for the different temperatures, presented in equation 3.5.

$$v = k_{lub} \cdot e^{\frac{b_{lub}}{T_{oil} + c_{lub}}} \tag{3.5}$$

Were:

- v - Kinematics viscosity [$mm^2\ s^{-1}$];
- K_{lub}, b_{lub}, c_{lub} - Lubricant constants;
- T_{oil} - Oil temperature [°C].

Variation of viscosity with pressure

For most lubricants, viscosity increases with the increase of pressure, as represented in Figure 3.4. This property has a great importance in the lubrication phenomenon, because it is fundamental in oil film formation.

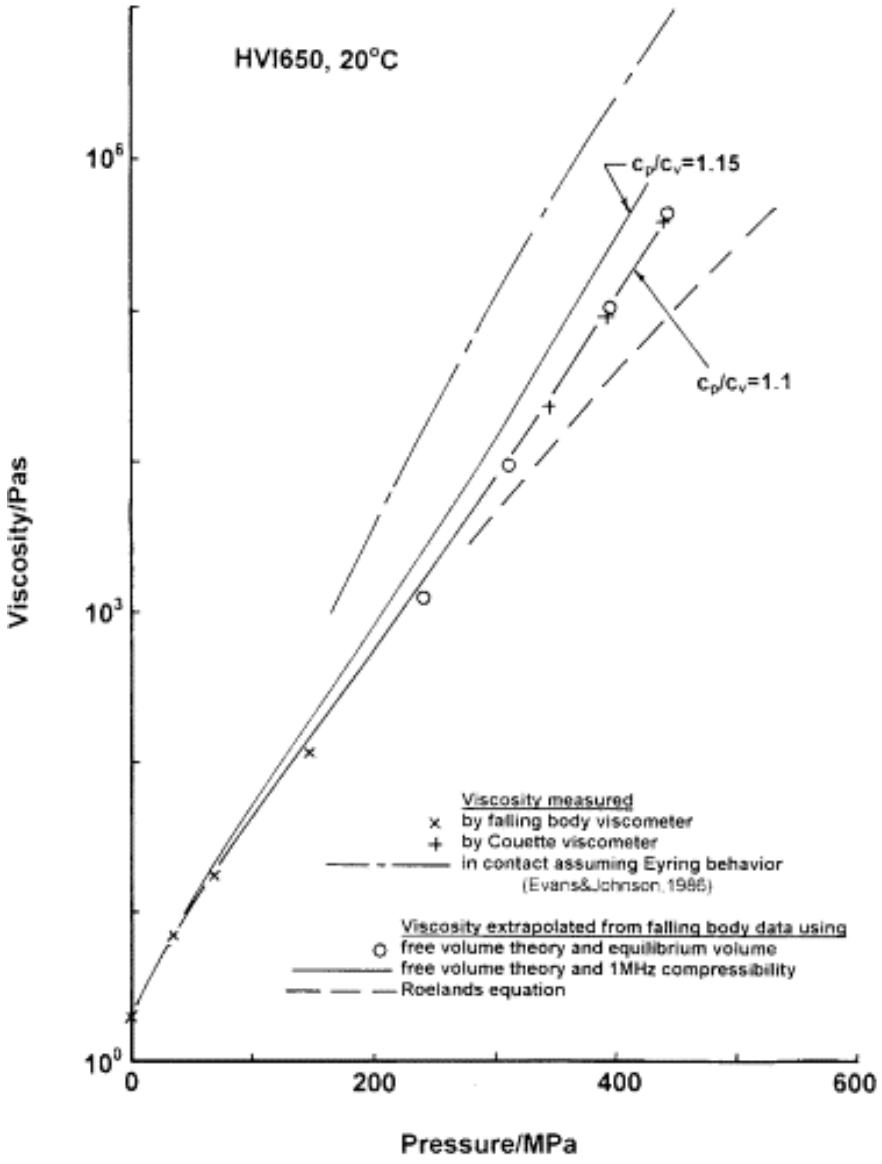


Figure 3.4: Viscosity variation of a mineral oil with pressure [19]

Variation of viscosity with shear rate

In the contact, the lubricants can achieve extreme high shear rates (10^6 to 10^7 s^{-1}). This effect viscosity reduction due to shear rate can be temporary or in some cases irreversible [11].

Pour Point

When a lubricant cools down, the viscosity can increase until it reaches values of 10^{12} Pa s. From a fixed temperature, glass transition temperature, the lubricant shows a behaviour close to an amorphous material. It is important to control this characteristic of the lubricant, because in specific conditions it can lead to an insufficient lubrication, reducing the life time of the components [11].

3.1.2 Density

The density of a lubricant is defined as its weight per unit volume. The variation of density with temperature is trifling, even so it can be defined by equation 3.6. Although this variation is small, the density influences the churning power loss, as it is one of the parameters that defines the amount of energy necessary to stir the lubricant.

$$\rho^T = \rho_0^T \cdot (1 + \alpha^{lub} (T - T_0)) \tag{3.6}$$

Where:

- $\boldsymbol{\rho^T}$ - Density of the lubricant at the required temperature **T** [kg m^{-3}];
- $\boldsymbol{\rho_0^T}$ - Density of the lubricant at the reference temperature $\mathbf{T}_0$ [kg m^{-3}];
- $\boldsymbol{\alpha_{lub}}$ - Thermal expansion coefficient.

However, the variation of density with pressure is meaningful and has a great influence on the oil film that is generated in the contact. According to Dowson, this variation can be expressed using equation 3.7 [11].

$$\rho^p = \rho_0^p \cdot \left(1 + \frac{0.6\, p}{1 + 1.7\, p}\right) \tag{3.7}$$

Where:

- $\boldsymbol{\rho^p}$ - Density of the lubricant at required pressure [kg m^{-3}];

- ρ_0^p - Density of the lubricant at atmospheric pressure [kg m^{-3}];
- **p** - Required pressure [GPa].

3.1.3 Thermal Conductivity

The thermal conductivity of a material is a measure of its ability to conduct heat and it presents a linear variation with the temperature. The property has a significant importance, as a lubricant should have a good heat transfer rate, in order to remove as much heat as possible from the contact.

3.2 Lubrication Requirements for Differentials

As explained in chapter 2.1.1, the hypoid gears have a few demands of lubrication, due to the high sliding velocities and the elliptical area of contact. Besides, the differentials are installed in vehicles that can be subjected to very demanding conditions such as, high speed, torque and temperature. On the other hand, nowadays losses due to friction and churning have also an appreciable importance. All these factors will create high demands for the lubrication [20].

Some organizations have already created some standards that aim to assure whether if a lubricant can, or not, fulfill the demands for specific applications such as hypoid gears.

Usually, the lubricants used in differential are either mineral or synthetic based oils. Due to its low costs and good properties of lubrication, mineral oils are still used nowadays. Mineral oils are extracted from petroleum and composed especially from hydrocarbons. The synthetic base oils are synthesised hydrocarbons and were developed to solve particularly hard lubrication problems. These oils have better thermal stability, resistance to oxidation between others advantages, when compared to mineral oils. The major problem is higher costs. To all of these base oils are then added additives, in order to improve some specific properties of lubricants.

3.2.1 Lubricant Additives for Differentials

Additives are chemical agents, that are added to base oils, in order to assure some specific properties to the lubricant, or just improve some characteristics of the base oil.

In this section, the main additives used in lubricants for differentials will be presented. It will be discussed the main demands for differential lubricants and

how to fulfill this requests [11, 21, 22].

Extreme Pressure

The principal purpose of oils is to lubricate and protect the surfaces that are in contact and have relative speeds between them, by creating an oil film between the moving surfaces. When the continuous film can no longer be maintained, metal to metal occurs, causing severe abrasion and seizure, welding and generation of wear particles. These wear particles will circulate in the oil, shortening the life of other components in the assembly, such as rolling bearings and other rubbing surfaces.

When the components are subjected to very demanding work conditions (over 700 MPa of contact pressure), in these case hypoid gears, due to the extreme pressures that are applied to the contact, the base oil does not provide the necessary oil film, that assures the protection of the surfaces, It is necessary to improve the lubricant specifications, by adding extreme pressure additives. These type of additives will avoid the welding of the surfaces that are subjected to sliding in the contact, by forming a chemical film between the rubbing gear surfaces.

These kind of additives are normally made of sulphurous, phosphorous or chlorinated compounds. However these chemicals can provoke some corrosion problems, mainly in copper, but also in iron alloys, so it should be carefully added to the lubricant, in order to obtain the right balance.

Corrosion Protection

The chemical reactions of extreme pressure additives added to the oil, can cause bearing and gear wear, reducing the lifetime of the differential. These additives will react especially with copper but also with iron alloys. To overcome this problem, lubricant additives, that will inhibit the corrosive tendencies should be added.

There are many additives that can be used, such as dithiophosphates, dithiocarbamates and sulphur products. Many of these additives can react the extreme pressure additives, changing the properties of the lubricant, therefore should be carefully selected.

Oxidation and Thermal Stability

The more demanding operating conditions of differentials, can generate higher oil temperatures, that can be observed to an average of 70 °C, but under severe conditions, it can achieve temperatures over 260 °C. As usually differentials do not have any type of temperature control, so it is necessary to use a more resis-

tant lubricant to such temperatures. These work conditions could induce a faster oil degradation, causing an extreme increase of viscosity and high insoluble contents, which may result in oil solidification at lower temperatures reached when it is still. Such phenomena will result in excessive wear of gears and bearings that are lubricated with the oil.

The problem of oxidation can be overcome with some chemical compounds as dithiophosphates, hindered phenol, nitrogen bases, between others. By adding the additives, a lubricant will not demonstrate such increase of viscosity and low percentages of pentane and benzane insolubles will be obtained.

Limited Slip Properties

As explained in section 2.2, limited slip differential has in addition to an usual rear axle, clutches that will alter the amount of torque that is applied to each one of the output shafts, in order to assure traction on both wheels. However, these clutches must allow low slip during corners.

If we are selecting a lubricant for a limited slip differential, it is important that it has developed for these operating conditions. The lubricant should allow a sufficient lubrication when the clutches are not engaged, but also assure that the clutches will not over split when these are engaged. So it is important to control the frictional properties of the lubricant.

The additives are made of zinc, Phosphorus, sulphur and chlorine compounds. It is always important to verify if the current properties of the lubricant are not changed by the addition of these additives.

Pour Point Depressants

As explained before, rear axles usually do not have any kind of temperature control. These mean that during the shut down, the oil temperature will match the ambient temperature. If this temperature is very low (subzero temperatures), the lubricant can reach temperatures below the pour point temperatures of the lubricant.

In order to overcome such a problem, pour point additives should be added to the lubricant. Pour point depressants are additives, which modify the wax crystallisation process, in such a manner that the oil will pour at lower temperatures. These additives are very efficient, and can drop the pour temperature by about 28 °C.

These chemicals are usually made of alkyl methacrylate polymer and copolymers, vinyl carboxylate-dialkyl fumarate copolymers between others.

Other additives

Usually a lubricant have over 50 properties that are assured by additives. It would be too thorough to present all of them, therefore the remaining important additives that are used in differential lubricants, as well as in other gears lubricants will be presented in a short list:

- **Viscosity Improvers** - The viscosity improvers will improve the viscosity index. They are used to increase the viscosity at higher temperatures and decrease the viscosity at lower temperatures, which provide a more stable viscosity;
- **Antiwear** - The antiwear additives will prevent the wear of the components that are rubbing, by creating a protect film in the metallic surfaces;
- **Antifoam** - This additive will decrease the amount of foam that a lubricant makes, when subjected to a strong agitation of the lubricant;
- **Detergent** - The detergent additives will help to reduce or prevent the amount of deposits in the lubricant, for any operating conditions;
- **Rust Inhibitor** - This additive will protect ferrous metals against rust.

3.2.2 Lubricant Service Designations

It is possible to conclude, that a lubricant can not be chosen just by it viscosity. The additives have an enormous influence in the lubricants properties that are not taken into consideration in the viscosity. Therefore some associations are responsible to certificate the lubricants, making sure that the demands for a specific work conditions are met.

Nowadays, the American Petroleum Institute (API) is the main association that is responsible to certificate lubricants for hypoid gears. The following service designations are in current use and they are designed for hypoid gears [23]:

- **API GL-4** - The API GL-4 designation is intended for axles with spiral bevel gears operating under moderate to severe conditions of speed and load, or axles with hypoid gears operating under moderate conditions of speed and load. For limited split differentials, the frictional requirement defined by the manufacturer should also be fulfilled. Lubricants with these designation can also be used in manual transmissions.
- **API GL-5** - The API GL-5 designation intended for gears, particularly hypoid gears, in axles operating under various combinations of high-speed/shock load and low-speed/high-torque conditions. For limited slip differentials, the frictional requirement defined by the manufacturer should also be fulfilled.

3.3 Methods of Lubrication for Differentials

In this section, the lubrication method that is usually used in differentials, oil bath lubrication, will be explained. Although oil circulation is rarely used in differentials, it will also be explained, as this lubrication method was used during the experimental tests. The idea is to try to simulate the lubrication conditions of oil bath with oil circulation. This tests will be better explained in chapter 5.

3.3.1 Oil Bath Lubrication

The majority of gearboxes are oil lubricated and easiest way is by oil bath lubrication, as it is economic, simple and reliable. This method does not need any external units, such as oil pumps, delivery or cooling systems. A continuous lubrication is assured by movement of the gears that are immersed in the oil bath, projecting the oil through the gearbox, as represented in Figure 3.5. The lubricant that is moving through the walls, can be conducted through a path, taking the oil to some specific location, as rolling bearings. The lubricant that sticks to the gear is carried to the other gears that are not immersed, assuring their lubrication.

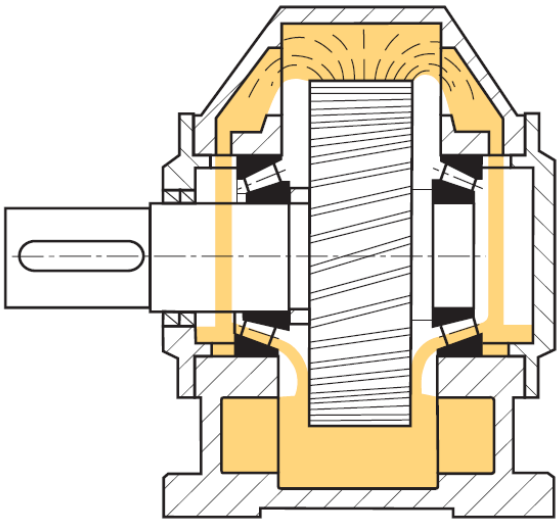


Figure 3.5: Oil bath lubrication [24].

But this method of lubrication has some limitations. The cooling of the system is assured by the heat transfer of the gearbox oil, which can not assure a stable control of the temperature. For low peripheral speeds, the projection of lubricant is not enough and for high speeds, the oil is over projected, so in both cases the lubrication is not assured. For spur gears, it is recommended to use this method of lubrication for peripheral speeds up to 20 m s^{-1}, without any additional designs.

The depth of immersion for hypoid or bevel gears, should always be the immersion of teeth over the entire width of the wheel [24].

3.3.2 Oil Circulation Lubrication

Usually, oil circulation lubrication is used for high-speed operations. The lubrication is assured by a pump that will take the oil to the components. In Figure 3.6, is possible to see this method applied to a rolling bearing.

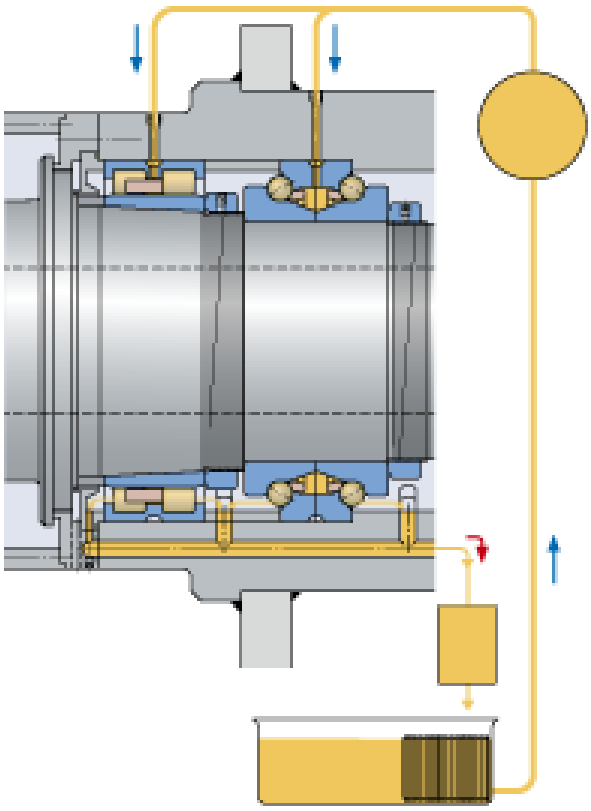


Figure 3.6: Oil circulation system in a rolling bearing [25].

The main advantages of this method is that, before the oil arrives to the components, it can be filtered and cooled down. The lubrication does not depend on the operational speeds, therefore it assures the lubrication at any condition. This means that with this method, the lubrication and the temperature of the gearbox are better controlled, assuring a better life time of its components. The disadvantages are the auxiliary equipment that is needed, such as oil pumps, cooling systems and delivery systems, so the costs will increase as the volume of the equipment [24, 25].

3.4 Selected Lubricant for Testing

In the experimental study that was devised the Total Transmission Dual 9 FE 75W-90 oil was used. This is an high performance synthetic oil developed for synchronized or non-synchronized manual gearboxes, reduction gears and axles with hypoid gears. This oil have the follow certifications:

- API GL-4;
- API GL-5;
- API MT-1;
- SAE J2360;
- MIL-PRF-2105E;
- MIL-L 2105 D.

According with Total [26], the benefits of this specific oil are:

- Reduced fuel consumption;
- Reduced cost of maintenance;
- Excellent antifoam, anticorrosion, antitrust properties;
- Very low loss in viscosity through shear;
- Excellent protection against wear and corrosion due to extreme-pressure properties of oil;
- Excellent stability in operation.

Table 3.1: Total transmission dual 9 FE 75W-90 characteristics [26].

Test	Unit	Test method	Result
Volumetric mass at 15ºC	kg m^{-3}	DIN 51757 D	866
Viscosity at 40ºC	mm^2 s^{-1}	ASTM D445	101
Viscosity at 100ºC	mm^2 s^{-1}	ASTM D445	15
Viscosity index	-	ASTM D2270	157
Viscosity Brookfield at -40ºC	mPa s^{-1}		66 000
Flash point	ºC	ASTM D97	-51
Pour point	ºC	ASTM D92	190

This oil has an high viscosity index, consequently it has a low viscosity variation with the temperature, as represented in Figure 3.7. To obtain this representation of lubricant used in the experimental tests, equation 3.3 from ASTM D341 standards was used. With the data presented in Table 3.1, it was possible to define the lubricant constants:

- m_{lub} - 2.9422;
- n_{lub} - 7.64469;
- a_{lub} - 0.7 $mm^2\ s^{-1}$.

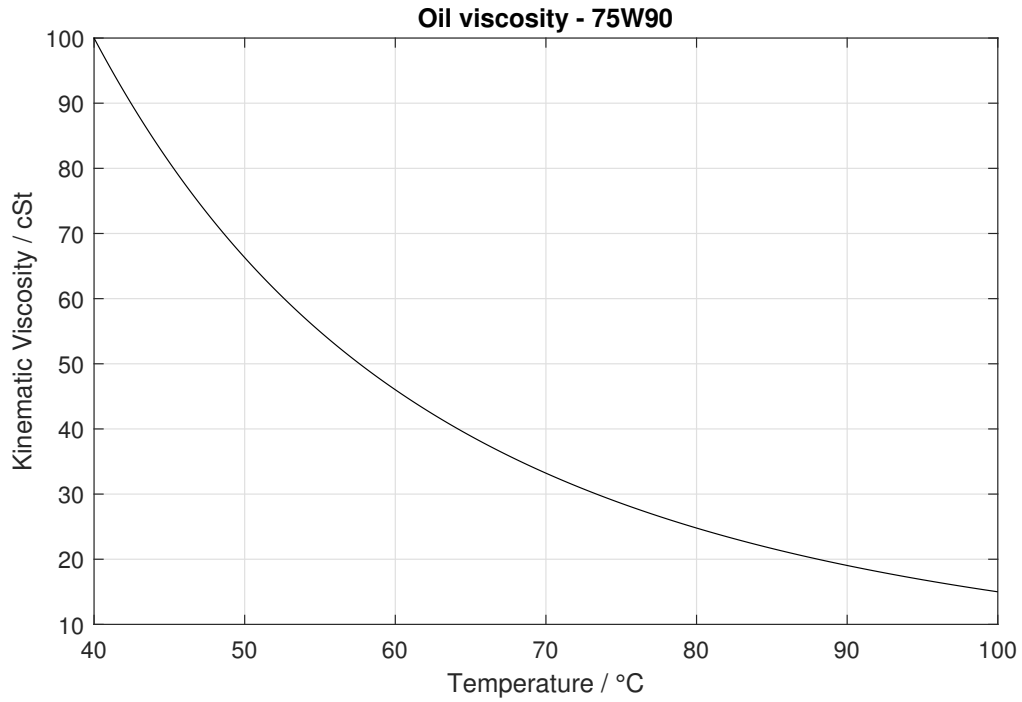


Figure 3.7: Kinematic viscosity variation.

In terms of density, the oils present a trivial variation with the temperature, therefore it will be despised. This variation can be observed in figure 3.8, where it was represented using equation 3.6. With some experimental work, it was possible to obtain the thermal expansion coefficient, $\alpha^{lub} = 7.29 \times 10^{-4}$.

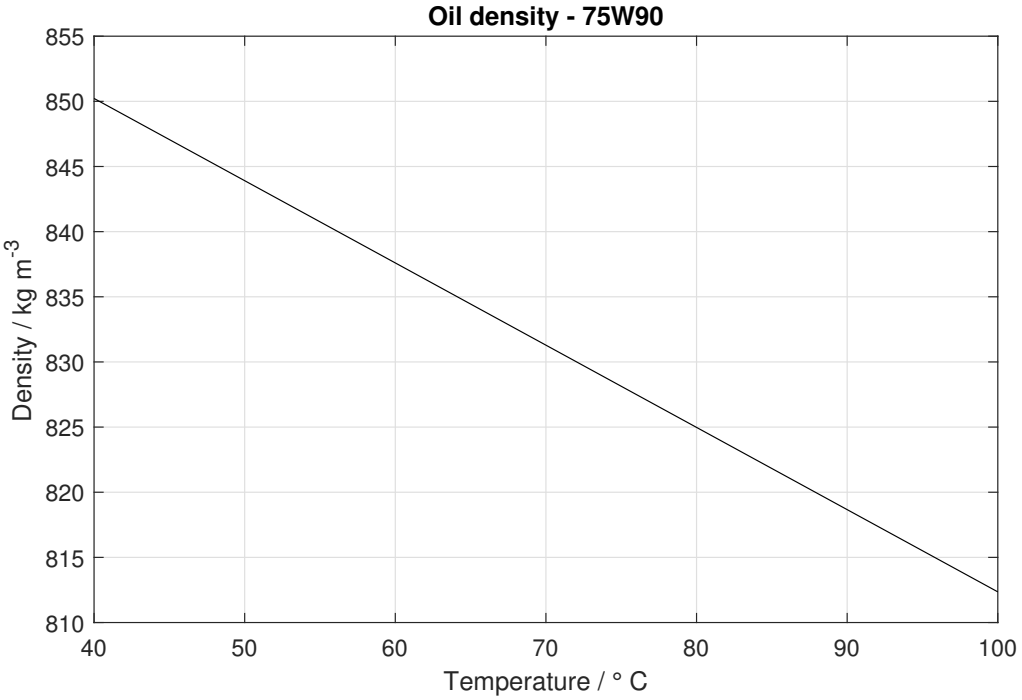


Figure 3.8: Density variation with temperature.

3.5 Lubricant Characterisation

Before starting the experimental tests in the rear axle, it is necessary to establish all the operating conditions. Therefore first the lubricant will be characterised, as it has a great influence on the power loss, using the Engler and SV-10 methods to obtain the viscosity for different temperatures and it will also be analysed the variation of the density with the temperature, using a DMA 35n densitometer.

The Engler viscosimeter is based on the analysis of the amount of time that takes a determinate volume takes to pass through an orifice, where both the volume of oil and the orifice are normalised (IP 212/92). This will allows us to measure the kinematic viscosity using equations that relate the measured time with the kinematic viscosity of the fluid. It is composed by container, that has an orifice, that is filled with a sample of the lubricant. This container has to be able to maintain the lubricant at stable temperature and it can be levelled. This test was done for three different temperatures.

The SV-10 is a device that can measure the lubricant dynamic viscosity almost in real time. This device has the ability to create vibration waves in one of the plates, and then measure the transmitted waves through the lubricant, analysing its viscosity. To do this measurement, a sample of lubricant was heated, and then the test is done until the lubricant cools down. Using the lubricant presented in section 3.4, it was possible to obtain the results presented in Figure 3.9.

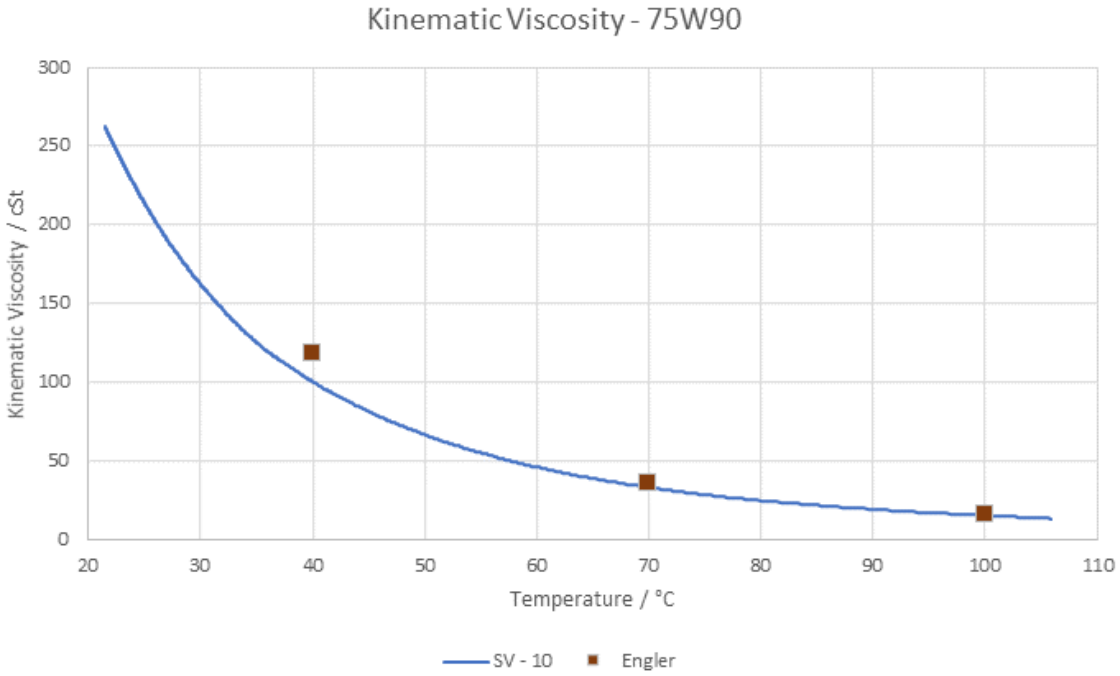


Figure 3.9: Viscosity result for 75W90 oil.

With this results, it was possible to obtain the following lubricant constants for the ASTM D341 formulation, presented in equation 3.3:

- m_{lub} - 2.91684;
- n_{lub} - 7.59600;
- a_{lub} - 0.7 $mm^2\ s^{-1}$.

It should be noticed that the constants are practically equal to the ones obtained using the information from the lubricant manufacturer, presented in section 3.4.

For the Vogel formulation, the following constants were obtained:

- K_{lub} - 0.10582;
- b_{lub} - 1011.57;
- c_{lub} - 104.168.

In order to obtain the density temperature curve a digital densitometer was used. Density measurements were taken at different temperatures resulting in the chart presented in Figure 3.10. The densitometer can only present an effective measurement up to a temperature of 40 °C. Therefore this test was done with

temperatures between 40 °C and room temperature. This test allows us to obtain the thermal expansion coefficient, $\alpha = 8.29 \times 10^{-4}$.

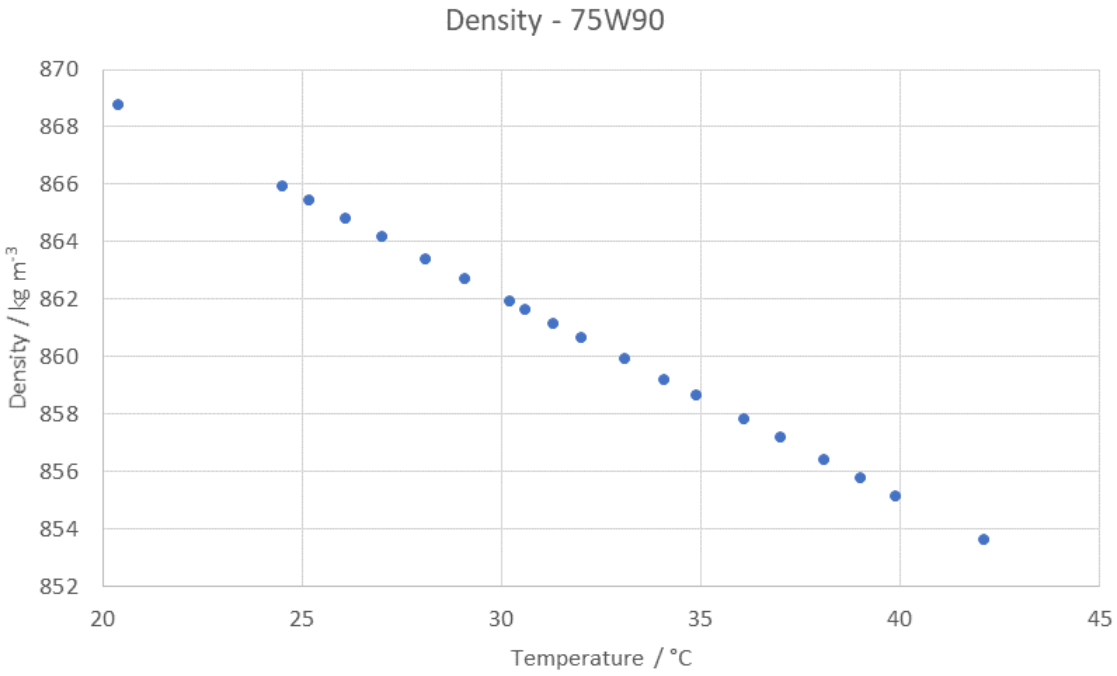


Figure 3.10: Density result for 75W90 oil.

4 Power Loss Models

The ability to predict the power losses of a mechanical system in our days, is a very important aspect, in order to reduce the energy consumption. In this chapter, it is presented the different power loss models that already were studied by other authors. With these models, it will be possible to validate them with experimental work, and if necessary present improvements to the models.

The total power loss of a differential can be considered the sum of the different losses. The components that are responsible for the losses are the rolling bearings, the seals and the gears. According to Höhn *et al.* [27], the total power loss is defined by equation 4.1, where the losses are divided by the different components and if it is possible by load dependent and load independent.

$$\overbrace{P_V}^{Power\ Loss} = \overbrace{\underbrace{P_{VZ0}}_{No-load} + \underbrace{P_{VZP}}_{Load}}^{Gears} + \overbrace{\underbrace{P_{VL0}}_{No-load} + \underbrace{P_{VLP}}_{Load}}^{Bearings} + \overbrace{\underbrace{P_{VD}}_{No-load}}^{Seals} + \overbrace{\underbrace{P_{VX}}_{No-load}}^{Auxiliary} \tag{4.1}$$

It is possible to divide the power loss of the gears and rolling bearings by the fact that if the loss is load dependent or not. The load dependent losses are the ones that depend of the load that is applied to the system, caused by the friction and sliding at the loaded gears contacts and rolling bearings. While load independent losses represent the losses that depend essencially of the rotational speed of the system and lubricant viscosity. This types of losses are an effect of friction of the seals, rolling bearings drag and auxiliary losses.

In a rear axle does not exist any auxiliary loss, as it does not have any kind of equipment, that will provide an external loss, such as oil pump.

4.1 Rolling Bearing

The no-load power loss of rolling bearings occurs because of the drag, caused by the movings parts in the lubricant. This types of losses are mainly related with the viscosity and density of the lubricant and the depth of immersion of the bearings in the oil level in the case of lubrication by oil bath. Although it is also related with type of bearing, rotational speed, type of lubrication, operating conditions and gearboxe internal design.

Load depend power loss in rolling bearings occurs because of the contact between components that transfer power. This kind of losses depend of transmitted load, friction coefficient and sliding velocities [28].

4.1.1 SKF Rolling Bearing Model

According to SKF, the rolling bearing losses are not constant and depends on certain tribological phenomena that occur in the lubricant film between the rolling elements, raceways and cages. Because of the type of lubricant film, we have four zones of lubrication, as represented in Figure 4.1.

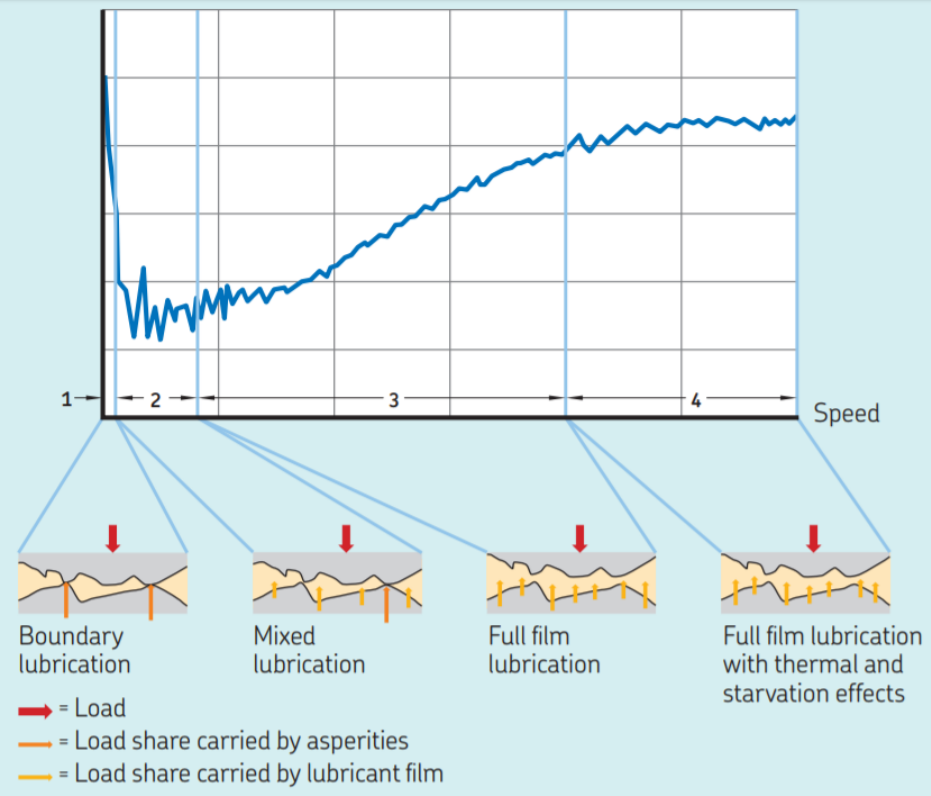


Figure 4.1: Bearing frictional moment as a function of speed [15].

The four zones are:

- **Zone 1 - Boundary lubrication condition,** in which only the asperities carry the load, and so friction between the moving surfaces is high.
- **Zone 2 - Mixed lubrication condition,** in which a separating oil film carries part of the load, with fewer asperities in contact, and so friction decreases.
- **Zone 3 - Full film lubrication condition,** in which the lubricant film carries the load, although viscous and friction losses increase.
- **Zone 4 - Full film lubrication with thermal and starvation effects,** in which the inlet shear heating and kinematic replenishment reduction factors compensate partially for the viscous losses, and so friction evens off.

In order to obtain an estimation of the frictional moment, it is used the SKF model present in equation 4.2, that follows the real behaviour of the rolling bearings and considers many internal and external influences [15].

$$M = M_{rr} + M_{sl} + M_{seal} + M_{drag} \tag{4.2}$$

Where:

- $\boldsymbol{M}$ - The total friction moment [N·mm];
- $\boldsymbol{M_{rr}}$ - The rolling frictional moment, and includes effects of lubricant starvation and inlet shear heating [N·mm];
- $\boldsymbol{M_{sl}}$ - The sliding frictional moments, and includes the effects of the quality of lubrication conditions [N·mm];
- $\boldsymbol{M_{seal}}$ - The frictional moment from integral seals [N·mm];
- $\boldsymbol{M_{drag}}$ - The frictional moment from drag losses, churning, splashing, etc., in an oil bath [N·mm].

In the specific case of a differential, the M_{seal} is null, because there are no seals in the bearings.

For paired bearings, the frictional moment can be calculated separately for each bearing and the results added together. The radial load is divided equally over the two bearings.

When the total frictional moment, M, is known, it is possible to obtain the rolling bearings power losses, using equation 4.3.

$$P_{VL} = \frac{2\pi \times 10^{-3}}{60} \cdot M \cdot n \tag{4.3}$$

Where:

- $\boldsymbol{P_{VL}}$ - Bearing frictional power loss [W];
- $\boldsymbol{M}$ - The total friction moment [N·mm];
- $\boldsymbol{n}$ - Rotational speed [rpm].

Rolling frictional moment

The rolling frictional moment is the torque loss of the rolling bearing, due to rolling its components, such as ball or rollers. It can be calculated using

$$M_{rr} = \phi_{ish} \cdot \phi_{rs} \cdot G_{rr} \cdot (v \cdot n)^{0.6} \tag{4.4}$$

Where:

- M_{rr} - Rolling fictional moment [N·mm];
- ϕ_{ish} - Inlet shear heating reduction factor;
- ϕ_{rs} - Kinematic replenishment/starvation reduction factor;
- G_{rr} - Geometric and load dependent variable for rolling;
- n - Rotational speed [rpm];
- v - Actual operating viscosity of the oil [$mm^2\ s^{-1}$].

Inlet shear heating reduction factor

When a bearing passes through the contact area, just a fraction of the overall quantity of oil is used to form a hydrodynamic film. So the rest of the oil is repelled and produces a reverse flow, as it is possible to see in Figure 4.2. This reverse flow shears the lubricant and generates heat, that will lower the oil viscosity and reduces the film thickness and rolling friction. This effect can be taking into account using the factor that can be obtained using equation 4.5.

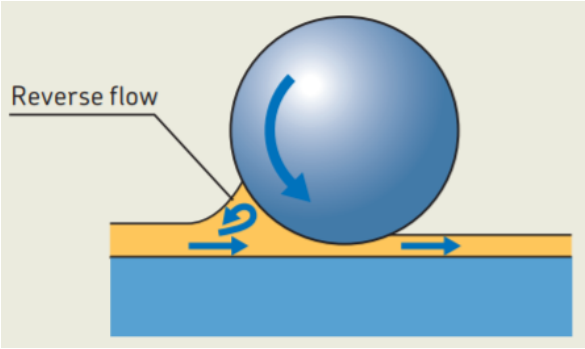


Figure 4.2: Reverse flow when a bearing passes [15].

$$\phi_{ish} = \frac{1}{1 + 1.84 \times 10^{-9} \cdot (n \cdot d_m)^{1.28} \cdot v^{0.64}} \tag{4.5}$$

Where:

- ϕ_{ish} - Inlet shear heating reduction factor;
- n - Rotational speed [rpm];
- d_m - Bearing mean diameter [mm];
- v - Actual operating viscosity of the oil [$mm^2\ s^{-1}$].

Kinematic replenishment/starvation reduction factor

When a rolling bearing is in rotation, the continuous over-rolling displaces excess lubricant from the raceways. If the viscosity or speeds are high, the lubricant may not have enough time to replenish the raceways, causing a "kinematic starvation" effect and reducing the thickness of the hydrodynamic film and rolling friction.

$$\phi_{rs} = \frac{1}{e^{\left[3\times10^{-8}\cdot v\cdot n\cdot(d+D)\cdot\sqrt{\frac{6}{2\cdot(D-d)}}\right]}} \tag{4.6}$$

Where:

- ϕ_{rs} - Kinematic replenishment/starvation reduction factor;
- v - Actual operating viscosity of the oil [$mm^2\ s^{-1}$];
- n - Rotational speed [rpm];
- d - Bearing bore diameter [mm];
- D - Bearing outside diameter [mm].

Geometric and load dependent variable for rolling

The geometric and load dependent variable for rolling depend of the bearing type, the bearing mean diameter and the radial and axial load. This value can be calculated using equation 4.7, for tappered roller bearings.

$$G_{rr} = R_1 \cdot d_m^{2.41} \cdot F_r^{0.31} \tag{4.7}$$

Where:

- G_{rr} - Rolling frictional variable;
- F_r - Radial load [N];
- F_a - Axial load [N];

- d_m - Bearing mean diameter [mm];
- Y - Axial load factor = 1.1;
- R_1 - Geometric constant = 2.60×10^{-6};
- R_2 - Geometric constant = 10.9.

Sliding frictional moment

The sliding frictional moment represent the resistive moment that occurs when the ball bearing slides over the raceways instead of rolling over. This moment can be calculated using equation 4.8.

$$M_{sl} = G_{sl} \cdot \mu_{sl} \tag{4.8}$$

Where:

- M_{sl} - Sliding frictional moment [N·mm];
- G_{sl} - Geometric and load dependent variable for sliding;
- μ_{sl} - Sliding friction coefficient.

Geometric and load dependent variable for sliding

Geometric and load dependent variable for sliding depend of the bearing type, the bearing mean diameter and the radial and axial load. For tapered roller bearings, it is possible to obtain the value of this variable using equation 4.9.

$$G_{sl} = S_1 \cdot d_m^{0.82} \cdot (F_r + S_2 \cdot Y \cdot F_a) \tag{4.9}$$

Where:

- G_{sl} - Sliding frictional moment [N·mm];
- F_r - Radial load [N];
- F_a - Axial load [N];
- d_m - Bearing mean diameter [mm];
- Y - Axial load factor.

Sliding friction coefficient

The sliding frictional coefficient can be obtained by interpolating between the μ_{bl} and μ_{EHD} using equation 4.10.

$$\mu_{sl} = \phi_{bl} \cdot \mu_{bl} + (1 - \phi_{bl}) \cdot \mu_{EHL} \tag{4.10}$$

Where:

- μ_{sl} - Sliding friction coefficient;
- ϕ_{bl} - Weighting factor for the sliding friction coefficient;
- μ_{bl} - Constant depending on movement:
  - = **0.12** for n ≠ 0;
  - = **0.15** for n = 0 (starting torque calculation).
- μ_{EHL} - Sliding friction coefficient in full-film conditions = 0.002 for tapered roller bearings.

Weighting factor for the sliding friction coefficient

The weighting factor for the sliding friction coefficient can be estimated using equation 4.11.

$$\phi_{bl} = \frac{1}{e^{2.6\times10^{-8}\cdot(n\cdot\nu)^{1.4}\cdot d_m}} \tag{4.11}$$

Where:

- n - Rotational speed [rpm];
- ν - Actual operating viscosity of the oil [$mm^2\ s^{-1}$];
- d_m - Bearing mean diameter [mm];

Frictional moment of seals

When bearings are fitted with contact seals, the seal losses can exceed the rolling bearings losses. This frictional moment can be calculated using equation 4.12, that includes both seals.

$$M_{seal} = K_{S1} \cdot d_s^{\beta_s} + K_{S2} \tag{4.12}$$

Where:

- M_{seal} - Frictional moment of seals [N·mm];
- K_{S1}, K_{S2}, β_s - Seal and bearing type constants;
- d_s - Seal conterface diameter [mm].

Once that the rolling bearing used in the differential are tapered rolling bearings, therefore the rolling bearing do not have seals, $M_{seal} = 0$.

Drag losses

As explained in the chapter 3, there are two main methods of lubrication, oil bath and oil injection, that influence the drag losses. This kind of losses are due to the resistance of the rolling elements moving through the oil and are very difficult to characterize, because of the external factors influence, such as external oil agitation, size and geometry of the oil reservoir, beyond the oil viscosity, bearing speed and oil level.

Oil bath lubrication

When oil bath lubrication is used, one part of the rolling bearing is always submerged. This means that exists a resistance of the rolling bearings moving through the oil and the drag losses should not be despised. The SKF model for calculating drag losses provides results with sufficient accuracy under the following conditions:

- The oil reservoir is large, therefore the effects from the size and geometry or external oil agitation are negligible;
- Horizontal shaft;
- The inner ring rotates at a constant speed;
- The speed does not exceed the permissible speed;
- The oil viscosity is within the limits:
  - ≤ 500 mm^2 s^{-1} when the rolling bearing is submerged up to, including, half of its outside diameter (oil level H $\leq$ D/2);
  - ≤ 250 mm^2 s^{-1} when the rolling bearing is submerged more than half of its outside diameter (oil level H > D/2).

The oil level H is measured from the lowest from the lowest contact point between the outer ring raceway and the rolling bearing element. For tapered roller bearings the lowest contact point can be estimated with sufficient accuracy using the outside diameter D.

The frictional moment of drag losses for roller bearings can be estimated using equation 4.13.

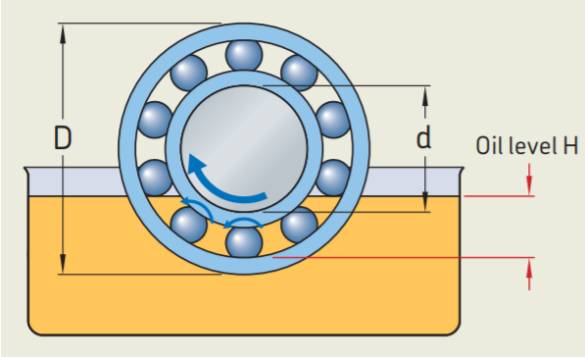


Figure 4.3: Reference oil level for the rolling bearing [15].

$$M_{drag} = 4 \cdot V_M \cdot K_{roll} \cdot C_W \cdot B \cdot d_m^4 \cdot n^2 \cdot + 1.093 \times 10^{-7} \cdot n^2 \cdot d_m^3 \cdot \left(\frac{n \cdot d_m^2 \cdot f_t}{v} \right)^{-1.379} \cdot R_5 \quad (4.13)$$

Where the roller element related constants and variables can be obtain using the following equations:

- $\boldsymbol{K_{roll}} = \frac{K_L \cdot K_Z \cdot (d+D)}{D-d} \cdot 10^{-12}$;
- $\boldsymbol{C_W} = 2.789 \times 10^{-10} \cdot l_D^3 - 2.786 \times 10^{-4} \cdot l_D^2 + 0.0195 \cdot l_D + 0.6439$;
- $\boldsymbol{l_D} = 5 \cdot \frac{K_L \cdot B}{d_m}$;
- $\boldsymbol{f_t} = \begin{cases} sin(0.5 \cdot t), & \text{when } 0 \leq t \leq n \\ 1, & \text{when } \pi < t < 2\pi \end{cases}$;
- $\boldsymbol{R_s} = 0.36 \cdot d_m^2 \cdot (t - \sin t) \cdot f_A$;
- $\boldsymbol{t} = 2 \cdot \cos^{-1}\left(\frac{0.6 \cdot d_m - H}{0.6 \cdot d_m}\right)$ When $H \geq 1.2 \cdot d_m, use\ H = 1.2 \cdot d_m$;
- $\boldsymbol{f_A} = 0.05 \cdot \frac{K_Z \cdot (D+d)}{D-d}$.

Where:

- $\boldsymbol{M_{drag}}$ - Frictional moment of drag losses [N·mm];
- $\boldsymbol{V_M}$ - Drag loss factor(Figure 4.4);

- B - Bearing width [mm];
- d_m - Bearing mean diameter [mm];
- d - Bearing bore diameter [mm];
- D - Bearing outside diameter [mm];
- H - Oil level [mm];
- K_Z - Bearing type related geometric constant = 6 for tapered roller bearing;
- K_L - Roller bearing type related geometric constant = 0.7 for tapered roller bearing;
- n - Rotational speed [rpm];
- v - Actual operating viscosity of the lubricant [$mm^2\ s^{-1}$].

Oil jet lubrication

For oil jet lubrication, the oil bath model should be used in this case, where the considered oil level is at half the diameter of the lowest rolling element and the drag loss should be multiplied by a factor of two. This method can give a good approximation, that does not take into account the influence of the rate and direction of oil flow. In the case of knowing the oil level H when oil is flowing and the bearing is at a stand-still, this value can be used directly in the drag loss calculation to obtain a more accurate estimate [15].

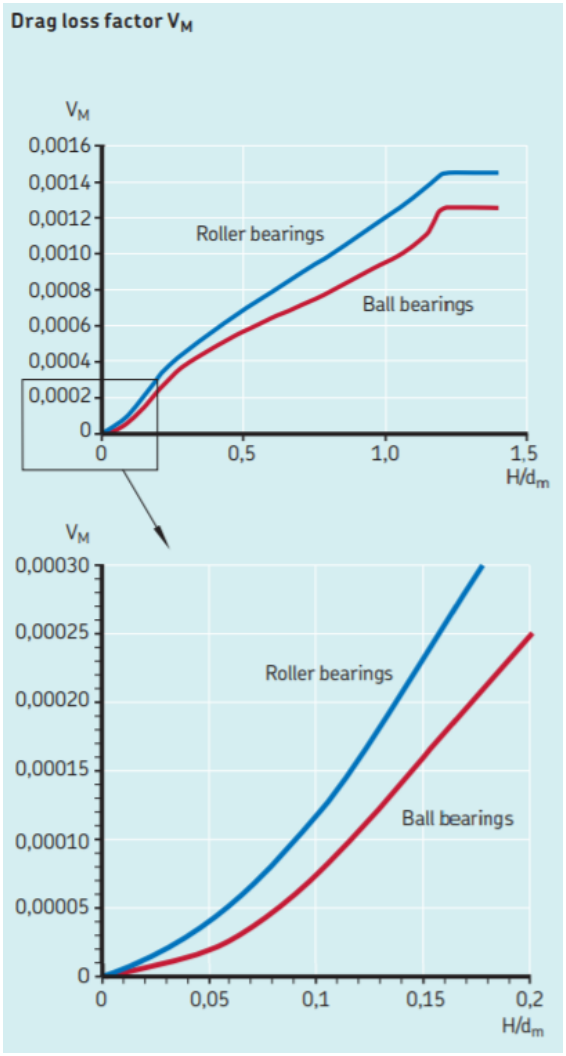


Figure 4.4: Drag loss factor [15].

4.1.2 ISO Rolling Bearing Model

ISO [29] has presented a simpler expression to obtain the power loss of rolling bearings.

$$M = M_0 + M_1 \tag{4.14}$$

Where:

- $\boldsymbol{M}$ - Rolling bearing torque loss [N·mm];
- $\boldsymbol{M_0}$ - Rolling bearing load independent torque loss [N·mm];
- $\boldsymbol{M_1}$ - Rolling bearing load dependent torque loss [N·mm].

Load independent

$$M_0 = f_0 \cdot 10^{-7} \cdot (v \cdot n)^{2/3} \cdot d_m^3 \tag{4.15}$$

Where:

- $\boldsymbol{M_0}$ - Rolling bearing No-load dependent torque loss [N·mm];
- $\boldsymbol{f_0}$ - Coefficient taking into account the bearing design and lubrication method;
- $\boldsymbol{v}$ - Actual operating viscosity of the lubricant [$mm^2\ s^{-1}$];
- $\boldsymbol{n}$ - Rotational speed [rpm];
- $\boldsymbol{d_m}$ - Bearing mean diameter [mm].

Load dependent

$$M_1 = \mu_1 \cdot f_1 \cdot F \cdot \frac{d_m}{2} \tag{4.16}$$

Where:

- $\boldsymbol{M_1}$ - Rolling bearing load dependent torque loss [N·mm];
- $\boldsymbol{\mu_1}$ - Friction coefficient dependent on load and bearing design =0.001;
- $\boldsymbol{f_1}$ - Coefficient taking into account direction of load application;
- $\boldsymbol{F}$ - Resulting bearing load = $\sqrt{F_r^2 + F_a^2}$ N;
- $\boldsymbol{d_m}$ - Bearing mean diameter [mm].

As it is being studied no-load power loss of a rear axle, the rolling bearings are only subjected to axial load from the preload, therefore $\boldsymbol{f_1}$ can be calculated using equation 4.17. According to the model author, the $\boldsymbol{f_0}$ for tapered rolling bearings is defined between 3 and 3.5. It was considered a value of 3 for this coeficient, during this dissertation.

$$\boldsymbol{f_1} = 2 \cdot Y \cdot \frac{F_a}{F} \tag{4.17}$$

4.1.3 Rolling Bearings Power Loss Models comparison

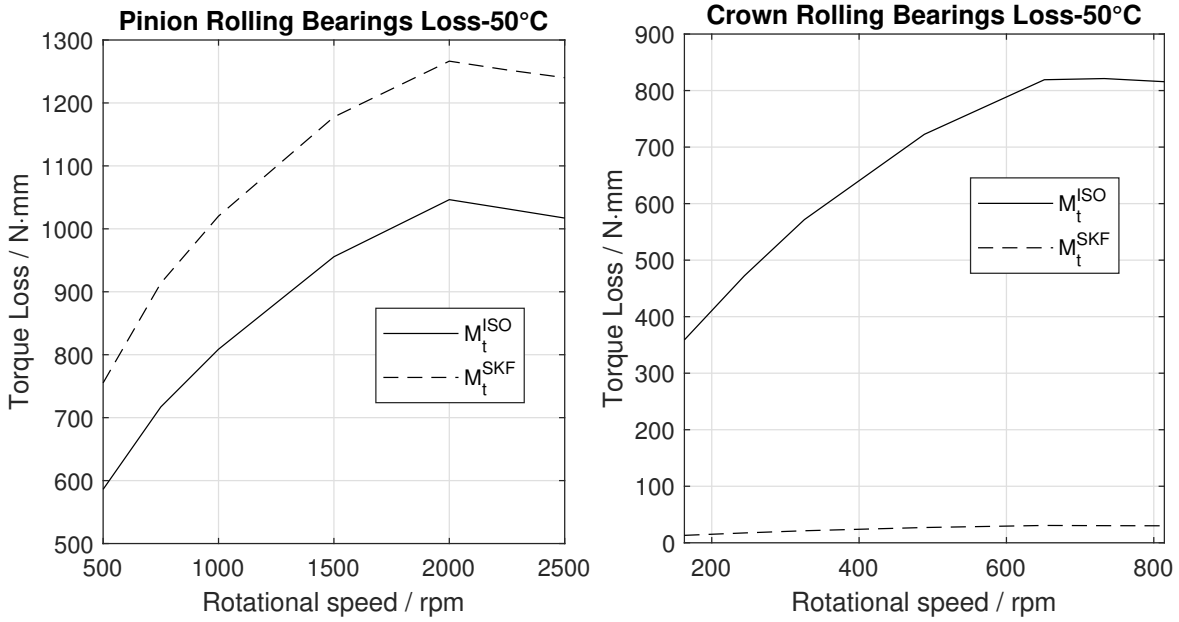
In order to perform this comparison, the differential rolling bearings presented in Table 2.2 will be considered. As it is not possible to measure the preload that the rolling bearings are subjected, it will be assumed a preload of 1000 N on the pinion rolling bearing. This value was obtained using a equation provided by SKF [15] that expresses the recommended preload, that was then round up to the 1000 N value.

$$F = k \cdot d \tag{4.18}$$

Where:

- $\boldsymbol{F}$ - Preload force [kN];
- $\boldsymbol{k}$ - Assembly rigidity factor = 0.02 for high rigidity demands;
- $\boldsymbol{d}$ - Bearing bore diameter [mm].

The crown wheel rolling bearings does not have preload, as the assembly just assure that there is no play. With all this data, it was possible to obtain the results presented in Table 4.5 at 50 °C, where the other temperature can be visualized in Appendix A.4.



(a) Pinion Rolling Bearings Torque Loss at 50 °C.

(b) Crown Wheel Rolling bearings Torque Loss at 50 °C.

Figure 4.5: Rolling bearings torque loss models comparison.

From this results, it is possible to verify that the SKF [15] presents a higher torque loss prediction and the same tendency for high preloads. For lower preloads,

it is possible to conclude that both models present different estimations, where the ISO [29] model presents a higher torque losses and different tendencies.

4.2 Seals

The seals, as one of the components that exert pressure on the shaft and have a relative velocity between the shaft and the seals, provoke a friction moment due to friction coefficient, therefore a power loss. Although it represents a small portion of the total power loss, in this chapter, some models that provide good approximations of the seals power loss will be introduced.

4.2.1 Croes

According to Croes *et al.* [30], the frictional losses in sealing elements is a phenomenon not yet well understood. The contact zone is a very small and the microscopic phenomenon is difficult to parameterize. The power loss can be calculated using equation 4.19.

$$P_{VD} = \frac{1}{2} \cdot \mu^{seal} \cdot F_R^s \cdot d_{sh} \cdot w \tag{4.19}$$

However, the main problem is to define the radial force F_R^s that the seal exerts on the shaft and the friction coefficient μ^{seal} that exist between the two materials. This parameters depend of many aspects, such as the type of atmosphere being sealed, differential pressure across the seal, tangential speed, ambient temperature and lubricant and method of lubrication [31].

4.2.2 Simrit

Simrit, a seal manufacturer, performed a large number of measurements and presented equation 4.20. It is a well known approximation and more easy to use, however it does not take into account many aspect in consideration [27].

$$P_{VD} = 7.69 \times 10^{-6} \cdot d_{sh}^2 \cdot n \tag{4.20}$$

Where d_{sh} is the shaft diameter and n is the rotational speed.

In Figure 4.6, it is possible to analyse the evolution of the seal power loss for different speeds and shafts diameters, using the same oil and corresponding temperature

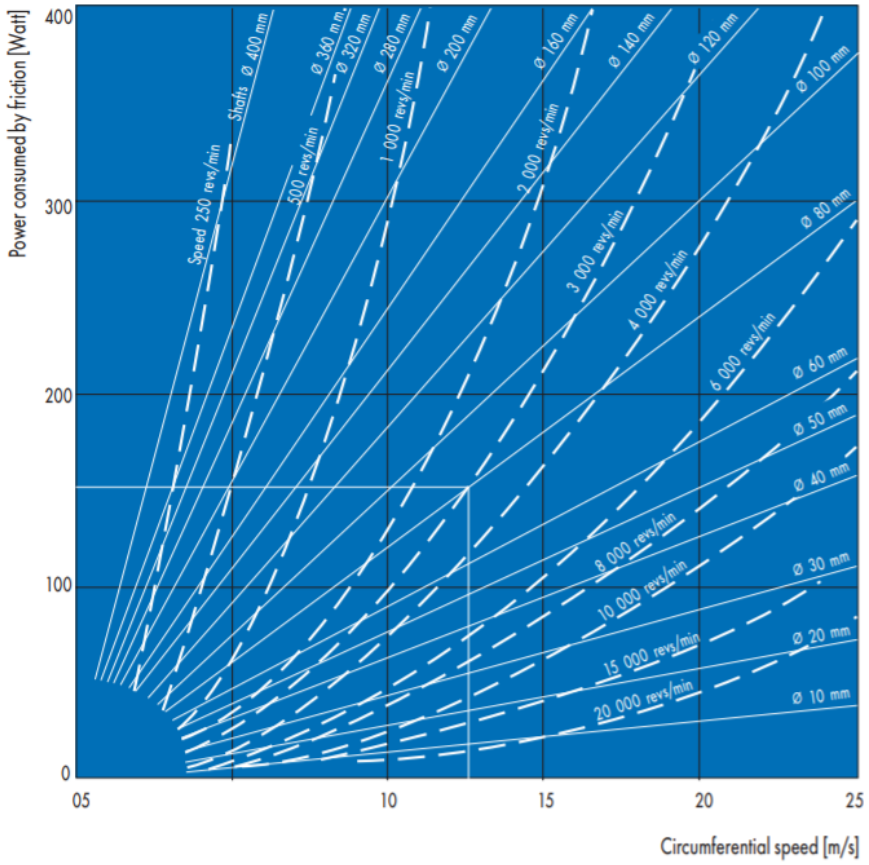


Figure 4.6: Friction loss on a seal in engine oil SAE 20, at T=100°C, v=85 cSt [32].

4.2.3 Linke

In order to take into account the influence of the oil viscosity (v) and temperature (K_{oil}) in the seals power loss, Linke [33], propose a variation of the Simrit formula presented in equation 4.21.

$$P_{VD} = [145 - 1.6 \cdot (K_{oil} + 273.15) + 350 \cdot \log\log(v_{40} + 0.8)] \times 10^{-7} \cdot d_{sh}^2 \cdot n \quad (4.21)$$

4.2.4 Kettler

Kettler [34], also developed a new equation 4.22 that also take into consideration the influence of the viscosity in the seal losses.

$$P_{VD} = 7.9163 \times 10^{-6} \cdot F_D \cdot d_{sh}^2 \cdot n \quad (4.22)$$

Where F_D expresses the effect of the temperature over the viscosity change.

More recently Bauer *et al.* [35], performed experimental tests on the power loss of lip seals and concluded that is almost impossible to accurately predict the frictional power loss. He explained that not only oil viscosity and seal pressure in the shaft influence the power loss, but also the shaft rugosity and wear at the sealing contact and even the assembly can have a great influence over the power loss.

4.2.5 Seals Power Loss Models comparison

In order to understand the differences between the different models, in Figure 4.7 it is possible to analyse Simrit and Linke models. This results were obtained for the pinion seal with a diameter of 45 mm, a 75W90 lubricant from Total and three different temperatures, 50, 70 and 90°C. The Kettler model was not took into consideration because of the difficulty of defining the effect of the temperature over the viscosity change, F_D.

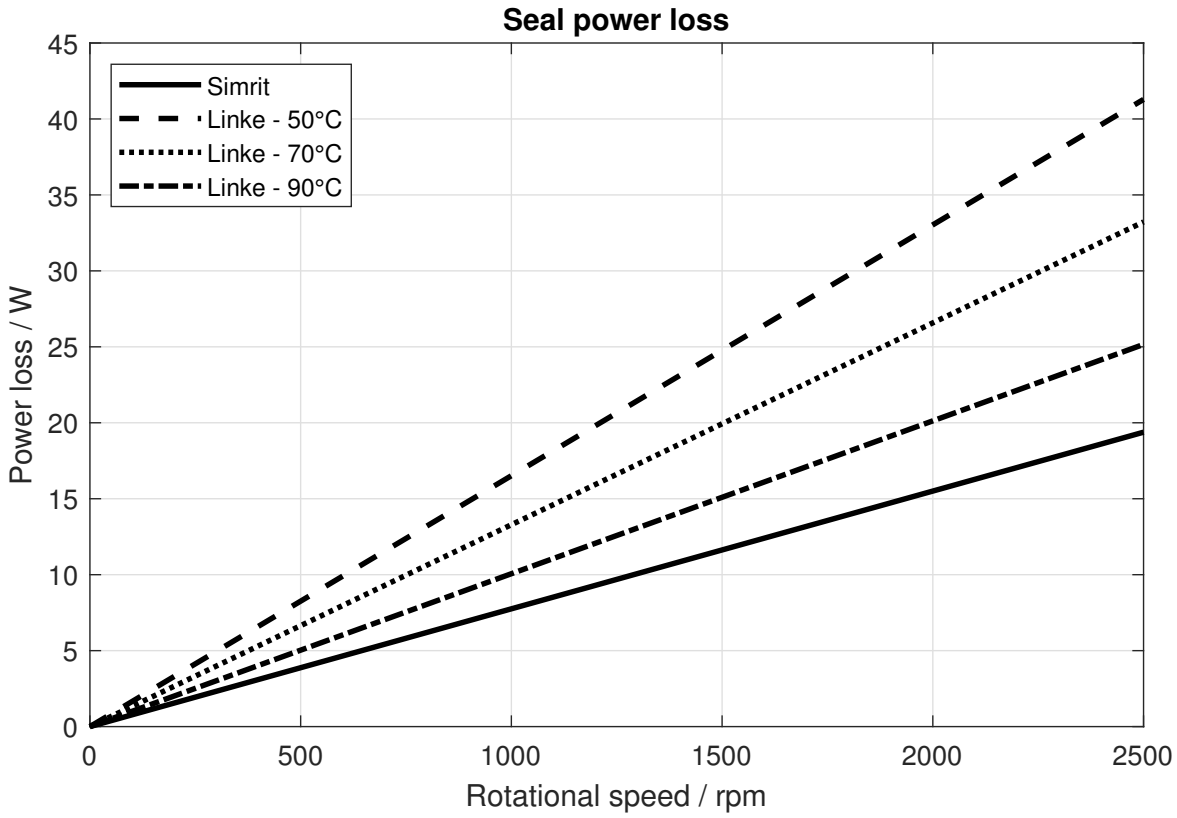


Figure 4.7: Seal power loss, using different model and temperatures for the pinion seal.

Its possible to conclude that the Simrit [32] model estimates the lower power loss and it is the simplest, as it does not depend of the oil temperature or viscosity.

4.3 Gears Churning

The churning power losses are defined as energy that is lost due to the fluid agitation provoked by the contact between fluids and a moving surface. However it represents a major contribute over the total power loss, it is responsible by lubrication of many components of a gearbox during its operation. This type of loss only exists in oil bath lubrication and can be divided in three categories: windage, churning and squeezing.

The windage power losses occur due to the interaction of a mechanical component and a single phase fluid that can be either air or lubricant. These losses evolve with rotational speed and become significant only for high tangential speeds or for fluids with high viscosity grades and densities.

The churning losses are similar to the windage losses, but involve at least two phases. These losses are the most important load independent power losses in geared transmissions: the majority of the gearboxes, in fact, are dip lubricated and, therefore, subject to churning losses.

The squeezing power losses are losses of a lower order of magnitude and arise due to the fact that cavity between two teeth is reducing its volume during the engagement causing pressure gradients and therefore, additional fluxes [31].

In this chapter, it will be introduced some of the most important churning models that are known, but it continues to be a topic hard to modulate, because this type of power loss shows the influence of many aspect that has not yet taken into account in this models, such as the gearbox design and other components of the gearbox that may stir the oil.

4.3.1 Terekhov

Terekhov [36] has realised some experimental test in order to understand the gears chruning losses. The main focus if this tests were to study the churning losses caused by high viscosities lubricants (200 to 2000 cSt) at low speeds and tested gears with modules ranging from 2 to 8 mm. With the obtained results it was possible to present the equation 4.23, as an attempt to predict the churning torque loss.

$$C_{ch} = \rho \cdot \omega^2 \cdot b \cdot r_p^4 \cdot C_m \tag{4.23}$$

Where:

- ρ - Lubricant density [kg m^{-3}];
- ω - Rotational speed [rad s^{-1}];

- b - Gear face width [m];
- r_p - Gear pitch radius [m].
- C_m - Dimensionless drag torque.

The dimensionless drag torque depends of the flow regime and can be calculated using equations 4.24 to 4.26.

1. For laminar flows (10 < Re < 2250):
   (a) If $\mathrm{Re}^{-0.6}\cdot\mathrm{Fr}^{-0.25} > 8.7\times10^{-3}$

$$C_m = 4.57\cdot Re^{-0.6}\cdot Fr^{-0.25}\cdot\left(\frac{h}{r_p}\right)^{1.5}\cdot\left(\frac{b}{r_p}\right)^{-0.4}\cdot\left(\frac{V_p}{V_0}\right)^{-0.5} \tag{4.24}$$

   (b) Otherwise:

$$C_m = 2.63\cdot Re^{-0.6}\cdot Fr^{-0.25}\cdot\left(\frac{h}{r_p}\right)^{1.5}\cdot\left(\frac{b}{r_p}\right)^{-0.17}\cdot\left(\frac{V_p}{V_0}\right)^{-0.73} \tag{4.25}$$

2. For turbulent flows (2250 <Re< 36000):

$$C_m = 0.373\cdot Re^{-0.3}\cdot Fr^{-0.25}\cdot\left(\frac{h}{r_p}\right)^{1.5}\cdot\left(\frac{b}{r_p}\right)^{-0.124}\cdot\left(\frac{V_p}{V_0}\right)^{-0.576} \tag{4.26}$$

Where:

- Re - Reynolds number for gears = $\frac{r_p^2\cdot\omega}{v}$;
- Fr - Froude number for gears = $\frac{r_p\cdot\omega^2}{g}$;
- h - Oil immersion depth [m];
- $\frac{V_p}{V_0}$ - Ratio of the submerged volume to the total lubricant volume.

4.3.2 Boness

Boness [37] has investigated the drag torque generated by the rotation of discs and gears in water or oil, and he developed equation 4.27.

$$C_{ch} = \frac{\rho}{2}\cdot\omega^2\cdot S_m\cdot r_p^3\cdot C_m \tag{4.27}$$

In the equation proposed by Boness [37], he has took into account the influence of the submerged area S_m, unlike Terekhov [36], that do not consider the influence of the oil level and submerged area. For equation 4.27, the dimensionless drag torque can be calculated using equations 4.28 to 4.30.

1. For laminar flows (Re< 2000):

$$C_m = \frac{20}{Re} \tag{4.28}$$

2. For intermediate flow regimes (2000 <Re< 100000):

$$C_m = 8.6 \times 10^{-4} \cdot Re^{\frac{1}{3}} \tag{4.29}$$

3. For turbulent flows (Re> 100000):

$$C_m = \frac{5 \times 10^8}{Re^2} \tag{4.30}$$

4.3.3 Höhn

The model presented by Höhn *et al.* [27], although it has considered the influence of the pair of gears and the design of the gearbox case, it has neglected the influence of the oil viscosity and density. According to Höhn [27], the churning torque loss can be calculated using the equation 4.31.

$$C_{ch} = C_{Sp} \cdot C_1 \cdot h^{C_2 \cdot \left(\frac{v_t}{v_{t0}}\right)} \tag{4.31}$$

Where:

- $\boldsymbol{C_{Sp}}$ - Splash oil factor;
- $\boldsymbol{C_{1,2}}$ - Factors;
- $\boldsymbol{h}$ - Oil immersion depth of gear [mm];
- $\boldsymbol{v_t}$ - Pitch line velocity [m s^{-1}];
- $\boldsymbol{v_{t0}}$ - Reference velocity = 10 m s^{-1};

From equation 4.32 to 4.35, it is possible to obtain the different factors needed to calculate the torque loss.

$$C_1 = 0.063 \cdot \left(\frac{h_1 + h_2}{h_0}\right) + 0.0128 \cdot \left(\frac{b}{b_0}\right)^3 \tag{4.32}$$

$$C_2 = \frac{h_1 + h_2}{80 \cdot h_0} + 0.2 \tag{4.33}$$

$$C_{Sp} = \frac{2 \cdot r_{o2}}{l_H} \cdot \left(\frac{4 \cdot h_2}{3 \cdot r_{o2}} \right)^{1.5} \tag{4.34}$$

$$l_H = \frac{4 \cdot (L_{housing} \cdot H_{housing})}{2 \cdot (L_{housing} + H_{housing})} \tag{4.35}$$

Where:

- $\boldsymbol{h_0}$ - Reference value of immersion depth = 10 mm;
- $\boldsymbol{h_1}$ - Immersion depth of gear 1 [mm];
- $\boldsymbol{h_2}$ - Immersion depth of gear 2 [mm];
- $\boldsymbol{b}$ - Gear face width [mm];
- $\boldsymbol{b_0}$ - Reference value of face width = 10 mm;
- $\boldsymbol{r_{o2}}$ - Outer radius of gear 2 [mm];
- $\boldsymbol{L_{housing}}$ - Housing width [mm];
- $\boldsymbol{H_{housing}}$ - Housing height [mm].

4.3.4 Changenet

More recently Changenet *et al.* [38], also presented a formula (equation 4.36) capable predict the churning torque loss in gears. This model depends essentially on the critical Reynolds number and centrifugal acceleration parameter. This author also confirmed the influence of the internal housing geometry of a gearbox and lubricant aeration.

$$C_{ch} = \frac{1}{2} \cdot \rho_{oil} \cdot \omega^2 \cdot r_p^3 \cdot S_m \cdot C_m \tag{4.36}$$

Where:

- $\boldsymbol{\rho_{oil}}$ - Oil density [kg m^{-3}];
- $\boldsymbol{\omega}$ - Angular velocity [rad s^{-1}];
- $\boldsymbol{r_p}$ - Pinion reference radius [m];

- S_m - Immersed surface area of the pinion [m^2];
- C_m - Dimensionless drag torque.

Using the theorem of Vaschy-Buckingham, it was possible to obtain the dimensionless drag group (equation 4.37) that depends of a five groups of parameters.

$$C_m = \psi_1 \cdot \left(\frac{h}{d_p}\right)^{\psi_2} \cdot \left(\frac{V_0}{d_p^3}\right)^{\phi_3} \cdot F_r^{\phi_4} \cdot Re_c^{\phi_5} \left(\frac{b}{r_p}^{\phi_6}\right) \tag{4.37}$$

Based on a large experimental data base, Changenet *et al.* [38] was capable to obtain equation 4.41 to 4.44, depending on the value of centrifugal acceleration (equation 4.38), Froud (equation 4.39) and critical Reynolds number (equation 4.40).

$$\gamma = w^2 \cdot (r_p \cdot b \cdot m)^{\frac{1}{3}} \tag{4.38}$$

$$F_r = \frac{r_p \cdot w^2}{g} \tag{4.39}$$

$$Re_c = \frac{r_p \cdot b \cdot w}{v_0} \tag{4.40}$$

1. if $\gamma < 750\ m\ s^{-2}$ and $\mathrm{Re}_c < 4000$

$$C_m = 1.366 \cdot \left(\frac{h}{d_p}\right)^{0.45} \cdot \left(\frac{V_0}{d_p^3}\right)^{0.1} \cdot F_r^{-0.6} \cdot Re_c^{-0.21} \cdot \left(\frac{b}{r_p}\right)^{0.21} \tag{4.41}$$

2. if $\gamma < 750\ m\ s^{-2}$ and $\mathrm{Re}_c > 4000$

$$C_m = 0.239 \cdot \left(\frac{h}{d_p}\right)^{0.45} \cdot \left(\frac{V_0}{d_p^3}\right)^{0.1} \cdot F_r^{-0.6} \cdot \left(\frac{b}{r_p}\right)^{0.21} \tag{4.42}$$

3. if $\gamma > 1250\ m\ s^{-2}$ and $\mathrm{Re}_c < 4000$

$$C_m = 20.797 \cdot \left(\frac{h}{d_p}\right)^{0.1} \cdot \left(\frac{V_0}{d_p^3}\right)^{-0.35} \cdot F_r^{-0.88} \cdot Re_c^{-0.21} \cdot \left(\frac{b}{d_p}\right)^{0.85} \tag{4.43}$$

4. if $\gamma > 1250\ m\ s^{-2}$ and $\mathrm{Re}_C > 4000$

$$C_m = 3.644 \cdot \left(\frac{h}{d_p}\right)^{0.1} \cdot \left(\frac{V_0}{d_p^3}\right)^{-0.35} \cdot F_r^{-0.88} \cdot \left(\frac{b}{d_p}\right)^{0.85} \tag{4.44}$$

Where:

- $\boldsymbol{h}$ - Oil immersion depth [m];
- $\boldsymbol{d_p}$ - Pitch diameter [m];
- $\boldsymbol{V_0}$ - Oil volume [m^3];
- $\boldsymbol{b}$ - Tooth face width [m];
- $\boldsymbol{m}$ - Module [m];
- $\boldsymbol{g}$ - Acceleration of gravity [m s^{-2}];
- $\boldsymbol{v_0}$ - Kinematic viscosity [m^2 s^{-1}].

It should be noted that an interpolation should be made between the equations when 750 m $s^{-2} < \gamma < 1250$ m s^{-2} [31].

In order to extend his formulation to helical gears, Changenet *et al.* [38] has deducted equation 4.45, as the vast majority of the results in the literature deals with spur gears. Based on experimental evidence, he found that for the same diameter and face width, churning power loss depends mostly on the immersed surface and not on the module.

$$S_m = r_p^2 \cdot (2\theta - \sin 2\theta) + d_b \cdot b \cdot \theta + 2 \cdot \frac{z \cdot \theta \cdot H_{tooth} \cdot b}{\pi \cdot \cos\alpha \cdot \cos\beta} \tag{4.45}$$

Where:

- $\boldsymbol{\alpha}$ - Pressure angle [rad];
- $\boldsymbol{\beta}$ - Helix angle [rad];
- $\boldsymbol{u}$ - Speed ratio.

The angle θ can be obtain according to Figure 4.8 and the churning power loss using formula 4.46.

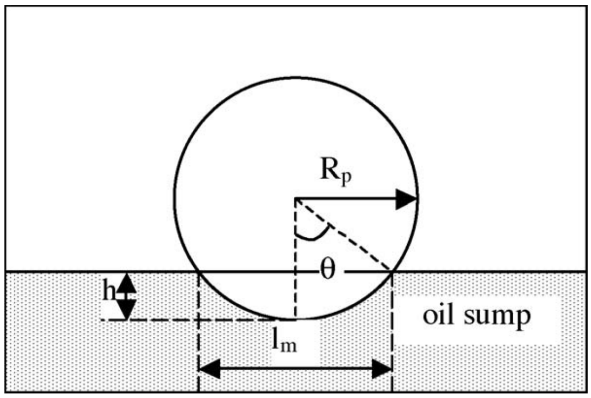


Figure 4.8: Geometrical data of the gear immersed surface [38].

$$P_{VZ0} = C_{ch} \cdot \omega \tag{4.46}$$

According to Changenet *et al.* [38], when we have clockwise rotation as expressed in Figure 4.9, the total churning losses of the pair of gears is given by the sum of each gear power loss. If the rotation is counter clockwise, it is not correct to assume the sum because of the sweel effect as expressed in Figure 4.10.

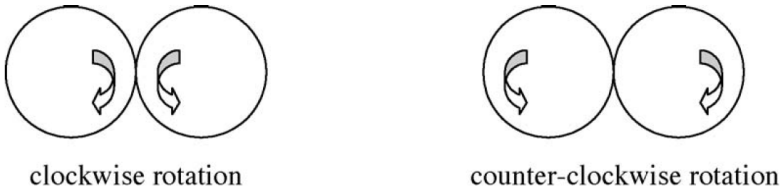


Figure 4.9: Definition of the senses of rotation [38].

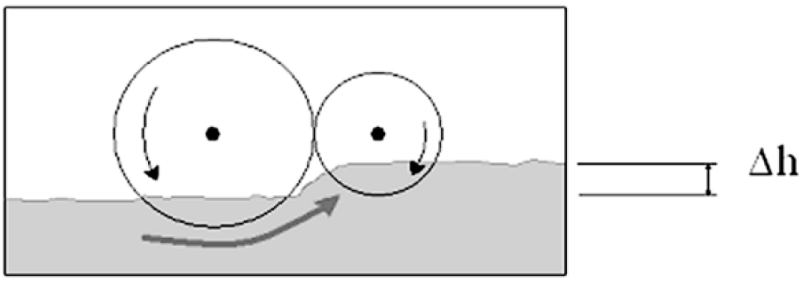


Figure 4.10: Schematic representation of the sweel effect [38].

Changenet *et al.* [38] propose equation 4.47, where we can calculate the variation of power loss due to the sweel effect.

$$\Delta P_{VZ0} = \frac{1}{2} \cdot \rho \cdot \omega^3 \cdot r_p^3 \cdot S_m \cdot \Delta C_m \tag{4.47}$$

$$\Delta C_m = 17.7 \cdot Fr^{-0.68} \cdot \frac{u-1}{u^8} \cdot \left[1 - \left(\frac{h}{r_p}\right)_{gear}\right] \tag{4.48}$$

Where:

- θ - Angle of the oil level in the gears [rad];
- Z - Number of teeth;
- H_{tooth} - Tooth height [m];

4.3.5 Fossier

More recently, Fossier [1] has made an investigation on the hypoid gear of truck axles. In this study, it was applied some correction to the Changenet [38] model, making it suitable for hypoid gears. The only changes were made in the dimensionless drag torque, that it is presented in equation 4.49 and 4.50.This model presented was made for hypoid gears, so it should present a better approximation with the results that will be obtained experimentally in this dissertation.

1. Re $\leq$ 20000:

$$C_m = 1.45 \cdot \left(\frac{h}{r_o}\right)^{0.15} \cdot \left(\frac{V_0}{r_o^3}\right)^{-0.20} \cdot Re^{-0.25} \cdot Fr^{-0.53} \tag{4.49}$$

2. Re $>$ 20000:

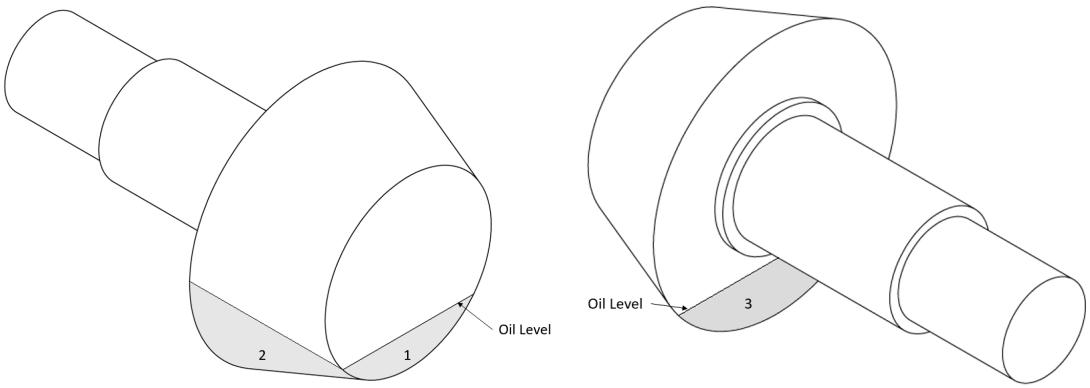
$$C_m = 1.12 \cdot \left(\frac{h}{r_o}\right)^{0.15} \cdot \left(\frac{V_0}{r_o^3}\right)^{-0.20} \cdot Fr^{-0.53} \tag{4.50}$$

4.3.6 Churning Torque Loss Models comparison

In order to better understand the existing churning power loss models, in this chapter it will be presented the estimated torque loss for the pinion and crown wheel, as well as a brief explanation on some values that were calculated. This study was performed only for the pinion and crown wheel, as the other components do not have any influence on the system, once this is a no-load test. Some information that was used in this chapter about the specifications of the pinion and crown wheel is presented in Table 2.1. To this comparison, it will be used the lubricant characteristics presented in section 3.5, that were obtained experimentally and the Höhn [27] model will not be used, as it only works for the pair of gears and we pretend to study each one of the churning losses individually.

Pinion

To use the Boness [37] and Changenet [38], it is necessary to know the submerged areas and volumes, as we are studying a hypoid pinion, we need to do some calculation in order to obtain this information. From direct measurements of the differential, it was possible to verify that the distance from the oil level until the pinion centre is 20 mm, defined as "a" variable and that the total oil volume is 1.25 l. The submerged areas will be divided in three different zones, as presented in Figure 4.11.



(a) Front view. **(b)** Back view.

Figure 4.11: Pinion submerged zones.

According to Mário [5], some parameters about the oil level in the pinion, can be obtained using 4.51 and 4.52. This parameters can be understand through Figure 4.12, which will be important to calculate the submerged area and volume.

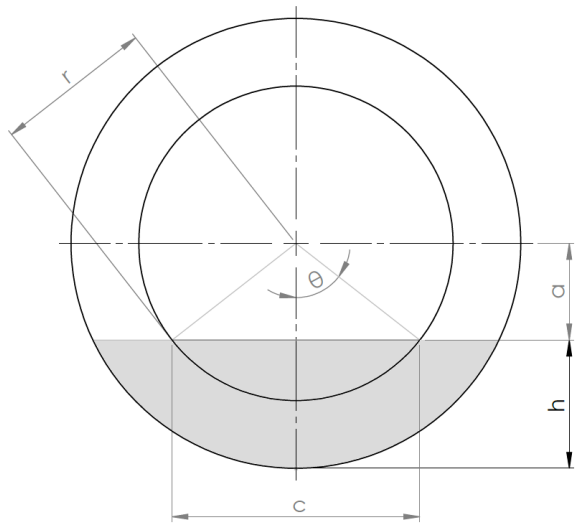


Figure 4.12: Pinion submerged area drawing.

$$\theta = \arccos\left(\frac{a}{r}\right) \tag{4.51}$$

$$c = 2 \cdot r \cdot \sin\theta \tag{4.52}$$

With the previously presented equations, it is now possible to apply equation 4.53 to obtain the area 1 and 3 ($A_{1/3}$), using the known expressions of the circular segment ($A_{Circ.Seg.}$) and triangle areas ($A_{\triangle}$).

$$A_{1/3} = A_{Circ.Seg.} - A_{\triangle} = \frac{1}{2} \cdot r^2 \cdot 2\theta - \frac{a \cdot c}{2} = r^2 \cdot \theta - \frac{a \cdot c}{2} \tag{4.53}$$

The area 2 is more complicated to obtain, as do not exist any formulation to calculate it. As a simplification, the influence of the teeth of the gears in this area will be disregarded. So one will assume the presence of a plain surface. To solve this problem, the area will be calculated using an area integral presented in equation 4.55, where the arc length is integrated. In Figure 4.13, it is possible to understand of the variables used in the integration.

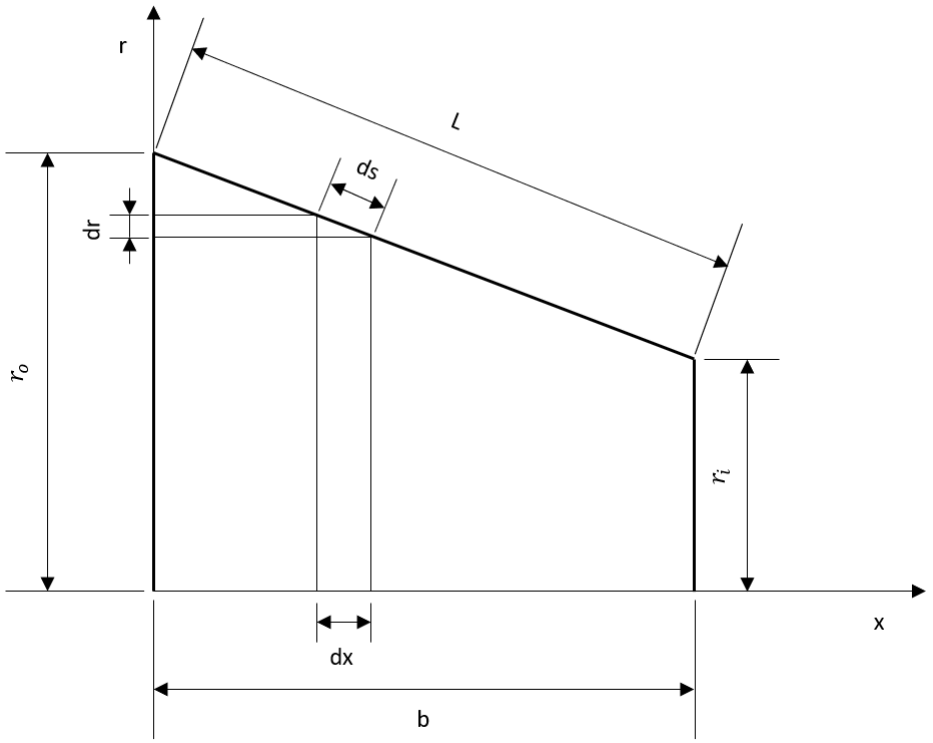


Figure 4.13: Schematic figure of the pinion.

$$L_{arc} = 2 \cdot r \cdot \theta \tag{4.54}$$

$$A_2 = \int_0^L 2 \cdot r(s) \cdot \theta(s)\, ds \tag{4.55}$$

As we do not have the necessary data to calculate the area, we have the necessity to rewrite this equation in order to the x variable, where it will be easier to solve. Applying the Pythagorean theorem, is possible to obtain the following equation:

$$A_2 = \int_0^b 2 \cdot r(x) \cdot \theta(x) \cdot \sqrt{1 + \left(\frac{dr}{dx}\right)^2}\, dx \tag{4.56}$$

Where the radius and the θ angle, can be obtained using the following equations:

$$r(x) = r_o - \frac{r_o - r_i}{b} \cdot x \tag{4.57}$$

$$\theta(x) = \arccos\left(\frac{a}{r_o - \frac{r_o - r_i}{b} \cdot x}\right) \tag{4.58}$$

In order to obtain the submerged volume, it is necessary to calculate the integral of the volume for this specific case. The area of the circular segment will be integrated over the length, were it is possible to deduct equation 4.60.

$$A_{surface}(x) = r(x)^2 \cdot \left(\theta(x) - \frac{1}{2} \cdot \sin(2\theta(x))\right) \tag{4.59}$$

$$V_{sub} = \int_0^b A_{surface}(x)\, dx \tag{4.60}$$

This integral can only be solved by numerical means, therefore it is necessary to use the MATLAB software in order to solve it.

After performing some calculations, it was possible to obtain the values presented in Table 4.1. This information will be useful to perform calculations within the scope of the previously presented models.

Table 4.1: Pinion results.

Parameter	Zone 1	Zone 2	Zone 3
a / mm		20	
r / mm	32.5	-	46.5
θ / rad	0.91	-	1.13
c / mm	51.24	-	83.96
Submerged Area / m^2	4.49×10^{-4}	2.79×10^{-3}	1.60×10^{-3}
Total Submerged Area / m^2		4.84×10^{-3}	
Submerged Volume / m^3		3.77×10^{-5}	

Crown Wheel

The crown wheel presents a more complex design, consequently it was necessary to divide the zone 2, in 3 different surfaces, as represented in figure 4.14. It should be noticed that this figure is not in scale and surface 3 represents the teeth of the crown wheel.

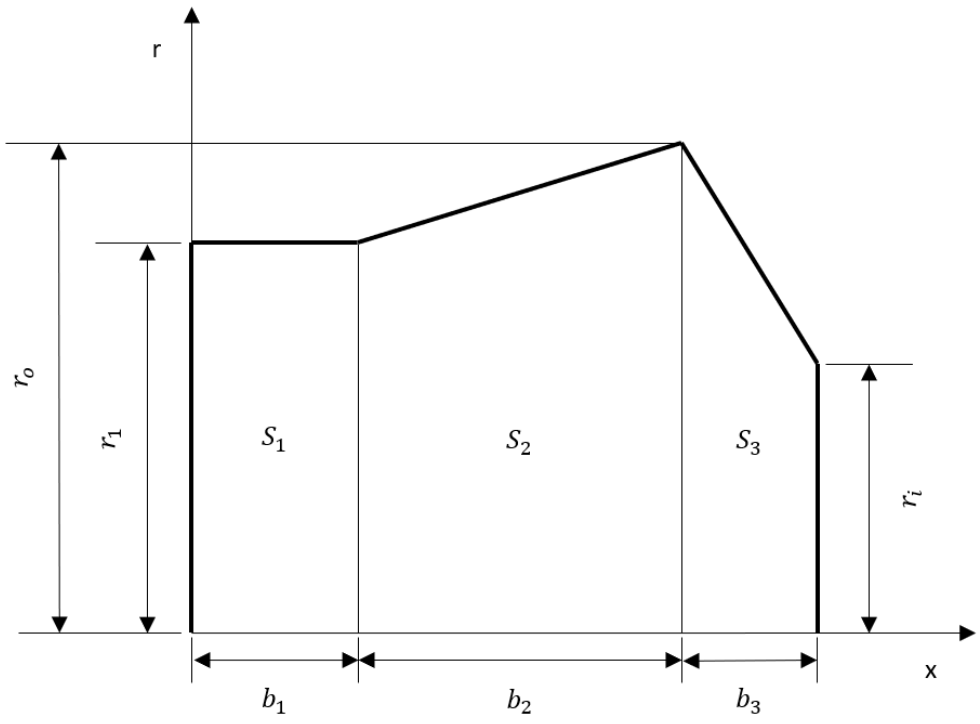


Figure 4.14: Crown wheel schematic figure of zone 2.

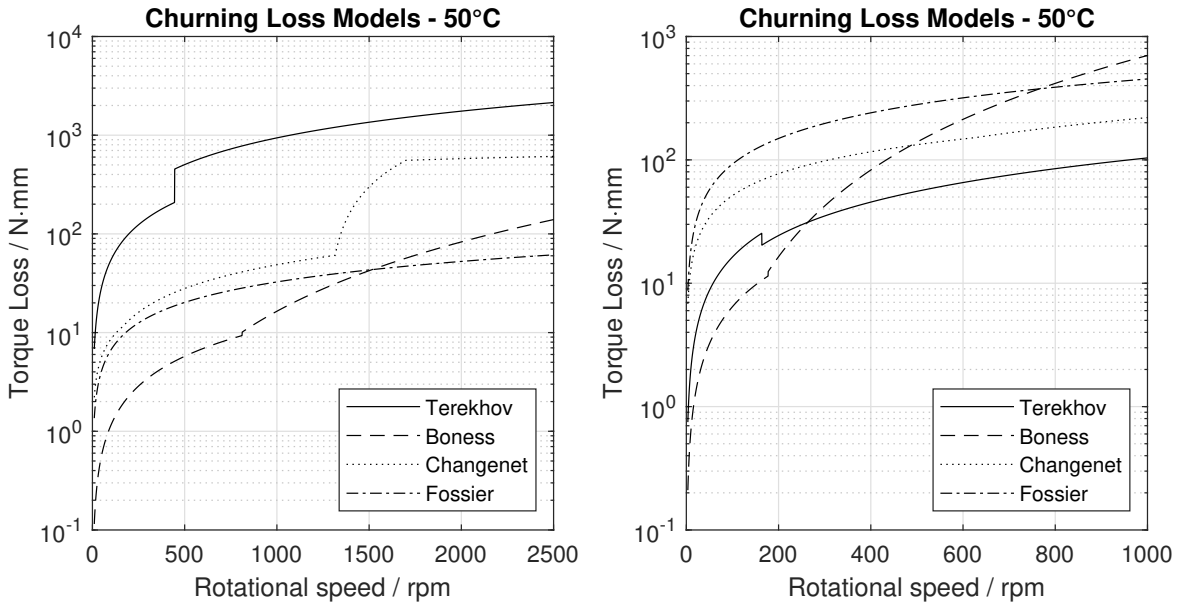
This means that it is necessary to apply equation 4.56 for each surface and then sum all, in order to obtain area 2 of the crown wheel. The same procedure has to be applied to equation 4.60 to calculate area 2.

The remaining parameters are calculated the same way as previously presented, and presented in Table 4.2. To obtain this results, it was considered that b_1 = 12 mm, b_2 = 21 mm and b_3 = 15 mm.

Table 4.2: Crown wheel results.

Parameter	Zone 1	Zone 2	Zone 3
a / mm		54	
r / mm	85	-	65
θ / rad	0.88	-	0.59
c / mm	131.03	-	72.36
Submerged Area / m^2	2.83×10^{-3}	9.30×10^{-3}	5.40×10^{-4}
Total Submerged Area / m^2		1.27×10^{-2}	
Submerged Volume / m^3		1.36×10^{-4}	

With this results, it was possible to obtain the estimation of the churning losses. In Figure 4.15, it is possible to visualise the prediction of the torque loss at 50 °C. In appendix A.1, it is possible to analyse the approximations, calculated for every operating condition. The Fossier [1] model is most recent and the only one that was particularly designed for differential gears, therefore it is the one that will be used to analyse the experimental results.



(a) Pinion torque loss at 50 °C. **(b)** Crown torque loss at 50 °C.

Figure 4.15: Churning torque loss models comparison.

5 Experimental Tests

5.1 Test Rig

The test rig used was developed to perform no-load tests on a planetary gearbox, and then it was adapted to perform tests to the BMW differential, that was presented in the section 2.3.

This test rig has the ability to collect all the necessary information, as torque, speed and working temperature. It also has a kinematic chain to assure the movement of the system and a temperature control unit to assure a stable oil temperature, either in the oil bath inside the differential or in a thermostatic oil bath that will be used in the oil circulation system. In Figure 5.1, it is possible to visualize some elements of the test rig, as the differential, torque transducer and some shaft couplings.



Figure 5.1: Test rig.

5.1.1 Differential

In the test rig, a differential from a BMW E46 318d was adapted, allowing to perform no-load experimental tests. This differential has a final reduction of 3.07 and its specifications can be observed in section 2.3. It is composed by the following components:

- **Crown wheel and pinion** - This set use hypoid gears, responsible to assure the necessary reduction to the mechanical system and provide a 90°power flux;
- **Planetary gear set** - These gears assure the differential function, allowing the vehicle to corner properly;
- **Tapered roller bearings** - The hypoid gears demand high rigidity of the assembly, that can only be assure by tapered roller bearings, subjected to an high preload.
- **Seals** - The used differential is composed by a pinion seal and 2 output shaft seals, that will assure that there is not any exterior contamination and any lubricant leak.

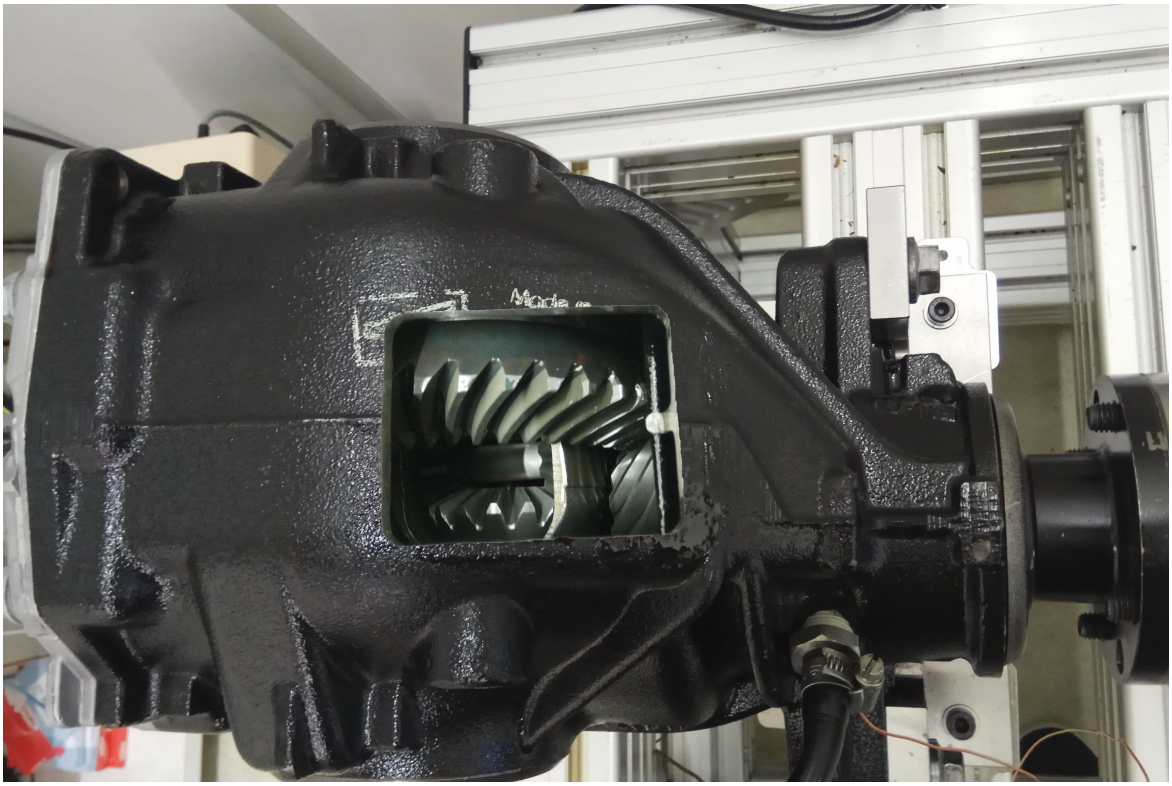


Figure 5.2: Differential top view.

5.1.2 Kinematic Chain

The kinematic chain in the test rig is composed by an electric motor, a belt drive train and some shaft couplings.

The 10 hp motor installed in the test rig can provide a maximum speed of 2920 rpm when providing a nominal frequency of 50 Hz. A 400 V nominal voltage is

provided to the motor. To control the speed of the driving motor, a speed variator which provides a variable frequency is used.

The drivetrain is composed by a timing belt that transfers the movement of the motor and also assures a multiplication of the speed of 3. The shaft couplings are used to provide a more flexible connection between the shafts. This system is shown in Figure 5.3.

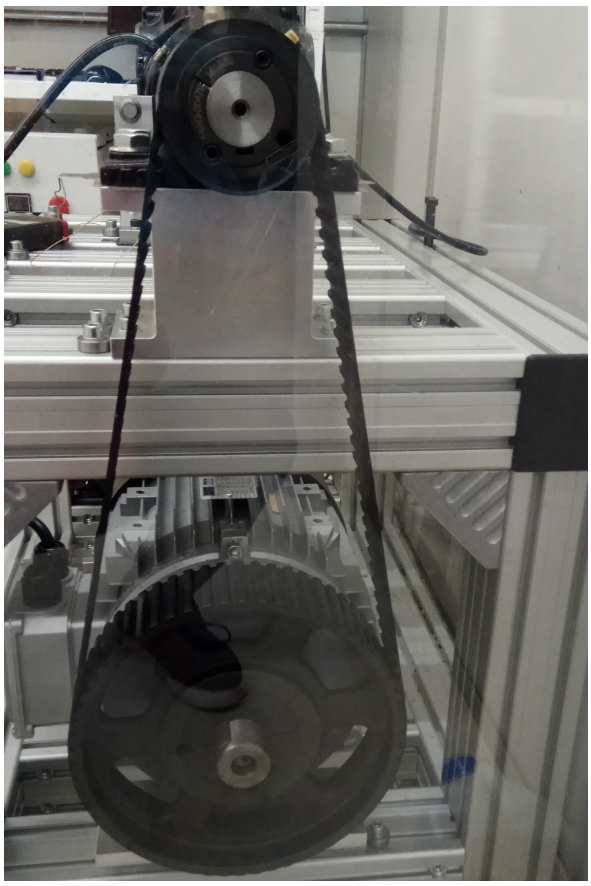
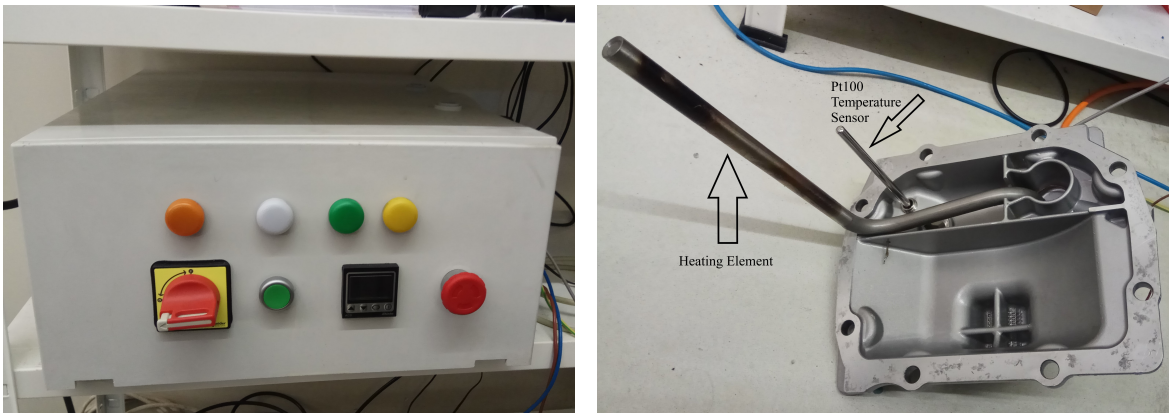


Figure 5.3: Belt drivetrain.

5.1.3 Temperature Control Unit

A explained before, the test rig has 2 different temperature control systems, that allows a stable control of the temperature for both lubrication methods used during the experimental tests. The system that assures the temperature in the differential oil bath, is composed by a 1500 W heat element that is immersed in differential oil, providing the necessary heat to the system, a control unit responsible to control the heating element and a Pt100 temperature sensor that provides the necessary information to the control unit. All the components of this device can be observed in Figure 5.4a and in Figure 5.4b, it is also possible to understand both the heating element and temperature sensor position in relation to the differential.



(a) Temperature Control Unit.

(b) Heating element assembled in the differential cover.

Figure 5.4: Temperature control unit for oil bath lubrication.

When oil circulation lubrication is used, it is necessary to control the oil temperature that is provided to differential. Therefore a thermostatic oil bath is used, which can provide a stable oil temperature, as it can either heat or cool the oil, and an oil pump that assures the necessary oil flow rate, as observed in Figure 5.5.



Figure 5.5: Thermostatic bath.

5.1.4 Data Acquisition

During the experimental tests, it was necessary to record information, as torque, speed and temperature. The torque and speed information are measured by transducer. The signal is then read by a ValueMaster data acquisition device and sent to

a computer that will record all the information in real time, recording samples in a frequency of 10 Hz. The specifications of torque transducer are described in Table 5.1 and it is represented in Figure 5.6.

Table 5.1: Torque transducer Specifications.

Torque Transducer Type ETH DRDL-II-50-10-n	
Specification	Value
Nominal torque / N·m	50
Measurement range / N·m	10, 50
Non-linearity / %	< 0.1
Hysteresis / %	< 0.1
Accuracy / %	0.01
Temperature sensitivity / % K	0.01

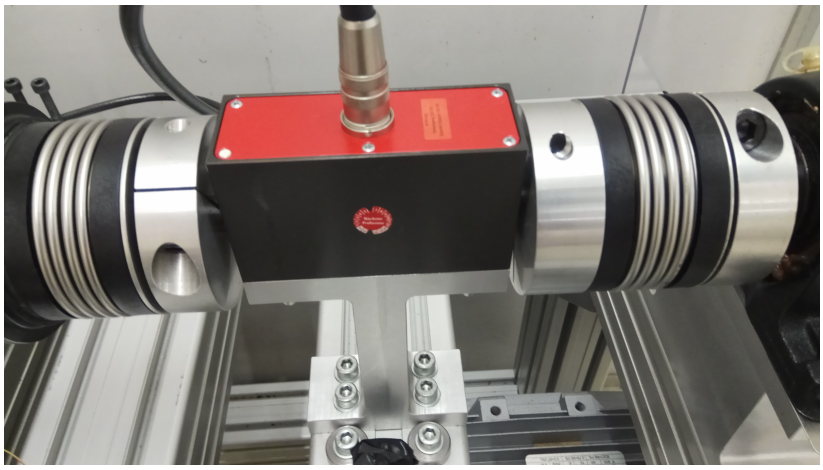


Figure 5.6: Torque transducer.

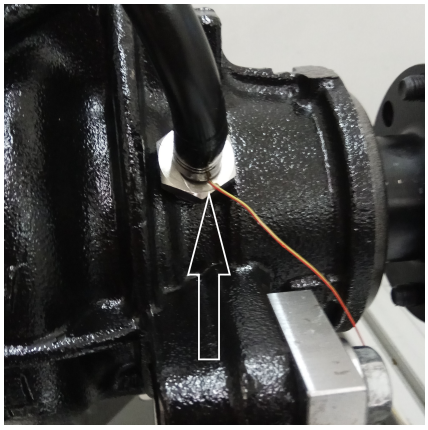
The temperature is recorded directly from a thermologger, that uses 2 type k thermocouple and its specifications are presented in Table 5.2. The temperatures are recorded from the differential oil bath and the end of the hose that assure the rolling bearings lubrication, as represented in Figure 5.7.

Table 5.2: Thermologger Specifications.

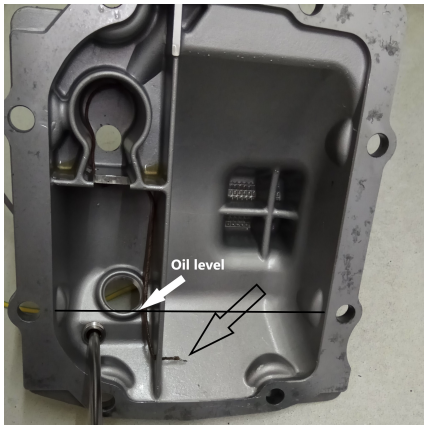
OMEGAETTE HH306 Thermologger		
Specification	Range	Value
Measurement range	-	-200°C ~ 1370°C
Resolution	-200°C ~ 200°C	0.1°C
	200°C ~ 1370°C	1°C
Accuracy	-200°C ~ 200°C	±(0.2% reading + 1°C)
	200°C ~ 400°C	±(0.5% reading + 1°C)
	400°C ~ 1370°C	±(0.2% reading + 1°C)
Sample rate	-	1.25 Hz



(a) OMEGAETTE Thermologger.



(b) Thermocouple responsible for measure the oil injection temperature.



(c) Thermocouple responsible for measure the oil bath temperature.

Figure 5.7: Temperature measurement system.

5.2 Test Parameters

In this section, it will be explained how the test parameters were chosen. In this parameters are lubricant temperature and speeds that will be used to perform the experimental tests.

5.2.1 Lubricant Temperature

As explained before, the losses in lubricated mechanisms depend of the oil viscosity. In order to evaluate this influence, it was selected linearly spaced viscosity intervals, instead of temperatures. This way, it is possible to analyze a vast range of viscosities. Since we are limited over the temperatures between 50 ºC and 90 ºC

because of the oil pump restriction due to the high viscosity (50 ºC) and the oil viscosity stabilization (90 ºC). As presented in Figure 5.8 and Table 5.3, it has selected an interval of approximately 8 cSt to obtain 7 different temperatures to perform the experimental tests.

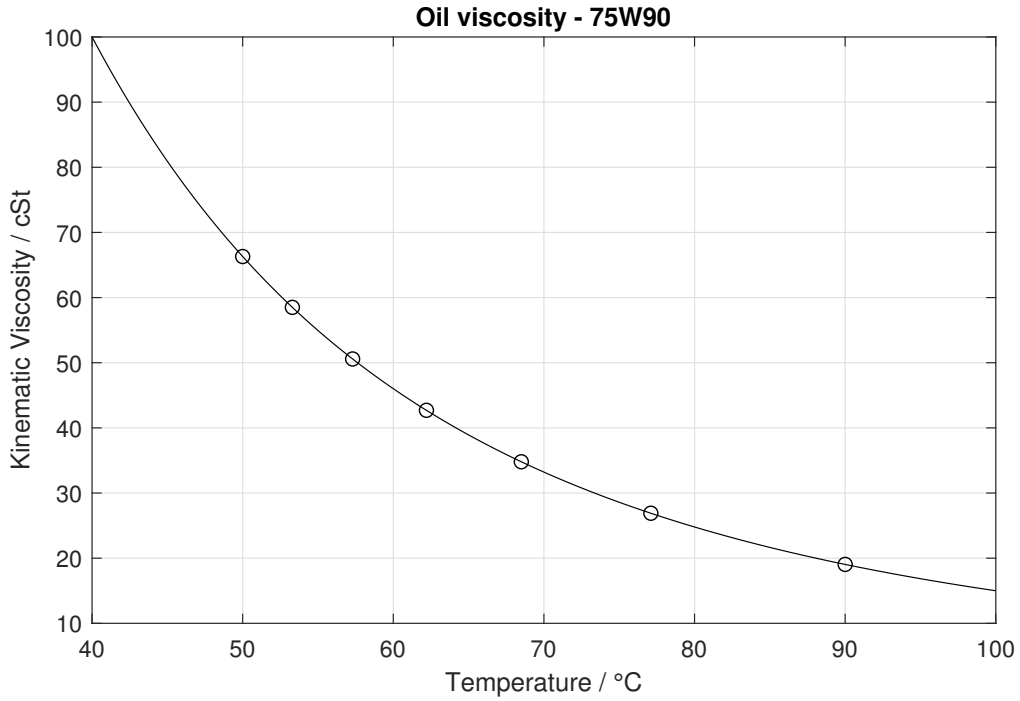


Figure 5.8: Selected temperatures over the kinematic viscosity variation.

Table 5.3: Selected temperatures.

T / °C	50.0	53.3	57.3	62.2	68.5	77.1	90.0
v / cSt	66.3	58.5	50.6	42.7	34.8	26.9	19.0

5.2.2 Rotational Speed

In this experimental study, the main objective is to replicate the operational conditions of the differential. In order to determine the pinion rotational velocity, we need first to relate the linear velocity of the vehicle with the rotational velocity of the wheel, using equation 5.1.

$$W_{wheel} = \frac{V_{lin}}{R_{tire}} \tag{5.1}$$

Where the rotational velocity depend of the linear velocity and the outer radius

of the wheel. To obtain the outer radius of the wheel, it was consulted the BMW manual and presented the relevant information in the Table 5.4.

Table 5.4: BMW E46 Rim and tire size [39].

Model	Standard			Option		
	Rim size	Tire size	Radius mm	Rim size	Tire size	Radius mm
323i	15 x 6.5	195/65R 15	317.25	16 x 7	205/55R 16	315.95
323Ci 325i/Ci 328i	16 x 7	205/55R 16	315.95	17 x 8	225/45R 17	317.15
328Ci	16 x 7	205/55R 16	315.95	17 x 7.5 17 x 8.5	225/45R 17 245/45R 17	317.15 326.15
330I/cI	17 x 7	205/50R 17	318.40	17 x 7.5 17 x 8.5	225/45R 17 245/45R 17	317.15 326.15
325xi 330xi	17 x 7	205/50R 17	318.40			

To calculate the rotational velocity of the wheel, it will be considered the average of all the different sizes of tires that can be used in a BMW E46, as a result, it is possible to obtain a radius of 318.48 mm.

Then, it is necessary to relate both rotational velocities, the wheels and the pinion velocities, that can be calculated using the gear ratio, obtained in equation 2.1.

$$W_{pinion} = W_{wheel} \cdot i_{final\ drive} \tag{5.2}$$

Finally it is possible to estimate the rotational velocity of the pinion with the linear velocity of the vehicle. The different chosen velocities to do the tests are presented in the Table 5.5.

Table 5.5: Different pinion rotational velocities.

Pinion rotational velocity / rpm	Linear velocity / km h^{-1}
500	≈ 20
750	≈ 30
1000	≈ 40
1500	≈ 60
2000	≈ 80
2250	≈ 90
2500	≈ 100

5.3 Rear Axle Experimental results

The main objective of this dissertation is to understand and modulate the power loss of a rear axle transmission, that can only be achieved with experimental work, in this case no-load experimental tests. So there is a necessity to obtain all the different losses separately, trying to understand all the phenomenon that are involved.

First it will be presented the total differential power loss, without the output shaft seals losses, as represented in equation 5.3. This test was performed with the components as presented in Figure 5.9 and oil bath lubrication was used as recommended by the differential manufacturer. During the experimental tests, the lubrication conditions will be documented, in order to understand the different lubrication *phenomena*. Due to the complexity of the assembly, it will not be possible to separate the churning losses from the rolling bearings losses.

$$P_{V0}^{Axle} = P_{VZ0}^{Crown} + P_{VZ0}^{Pinion} + P_{VL0}^{RB_C} + P_{VL0}^{RB_P} + P_{VD}^{Seal} \Leftarrow \text{Bath Lubrication} \tag{5.3}$$

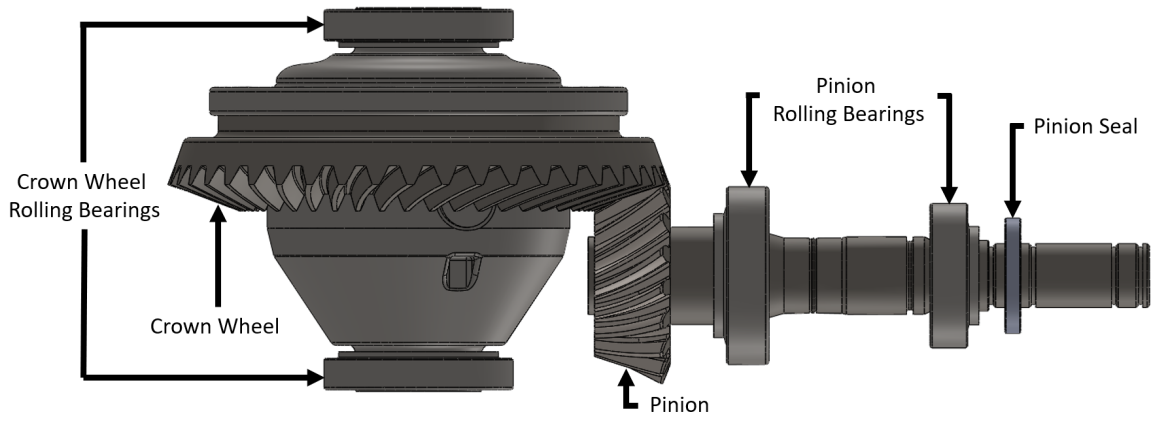


Figure 5.9: Assembly used during the first experimental test.

Then in order to evaluate the power loss of the pinion and its rolling bearings, the crown wheel was disassembled, as expressed in Figure 5.10 and the results are presented as observed in equation 5.4. For this test it was used the same lubrication conditions as in the total power loss test.

$$P_{V0}^{Pinion} = P_{VZ0}^{Pinion} + P_{VL0}^{RB_P} + P_{VD}^{Seal} \Leftarrow \text{Bath Lubrication} \tag{5.4}$$

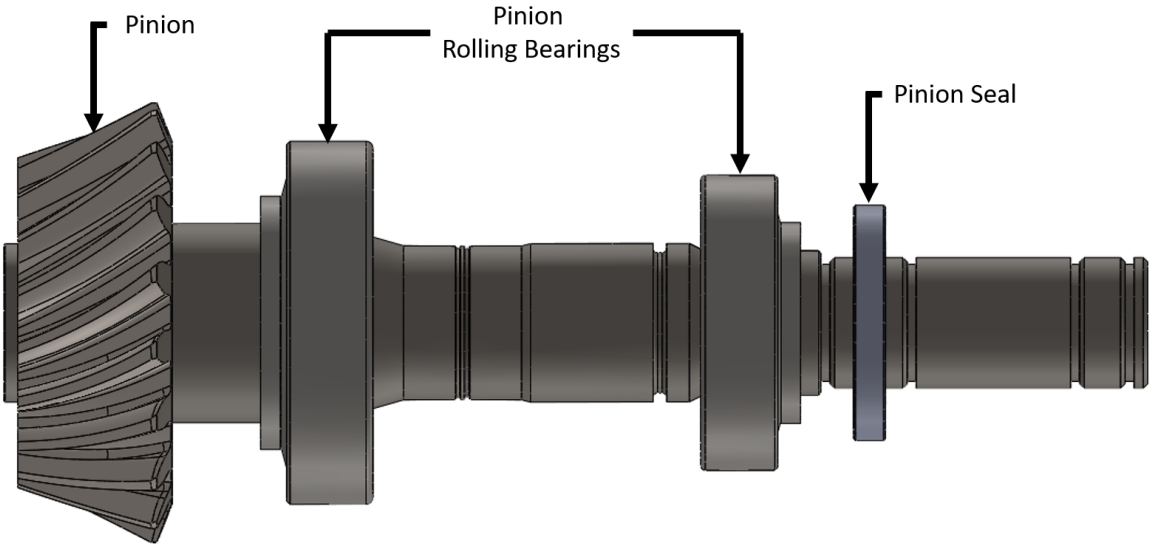


Figure 5.10: Assembly used during the second experimental test.

To obtain the rolling bearings losses, it was necessary to remove the pinion churning losses, therefore oil bath lubrication was replaced by oil injection. Due to difficulty of simulate the bath lubrication conditions, that the tests were performed, using an oil circulation system with variable flow rate, and two different attempts were done, as showed in equation 5.5. Due to the low contribution of the windage losses, caused by the contact between the moving gear and the air, these will be disregarded. To perform the tests using this lubrication method, it was necessary to plug the rolling bearing chamber, to assure that the oil will be trapped and the oil flow rate is assured to pass through the rolling bearings, as represented in Figure 5.11.

$$P_{r0}^{RB} = P_{VL0}^{RB_P} + P_{VD}^{Seal} \Leftarrow \text{Chamber isolation} \Leftarrow \begin{cases} \text{Minimum loss;} \\ \text{Overflow.} \end{cases} \tag{5.5}$$

First the pinion rolling bearings minimum power loss are obtained, where to obtain these results, different oil flow rates were tested to find the ideal lubrication condition.

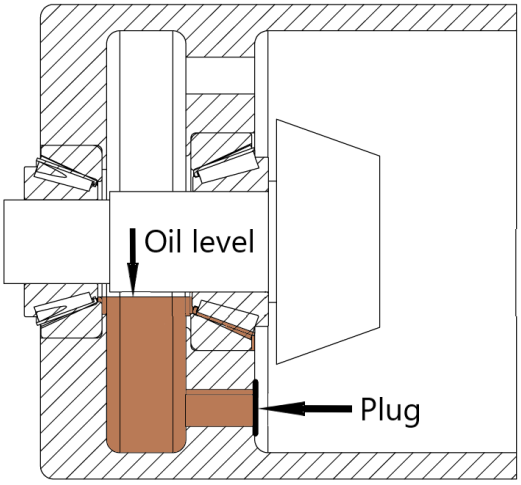
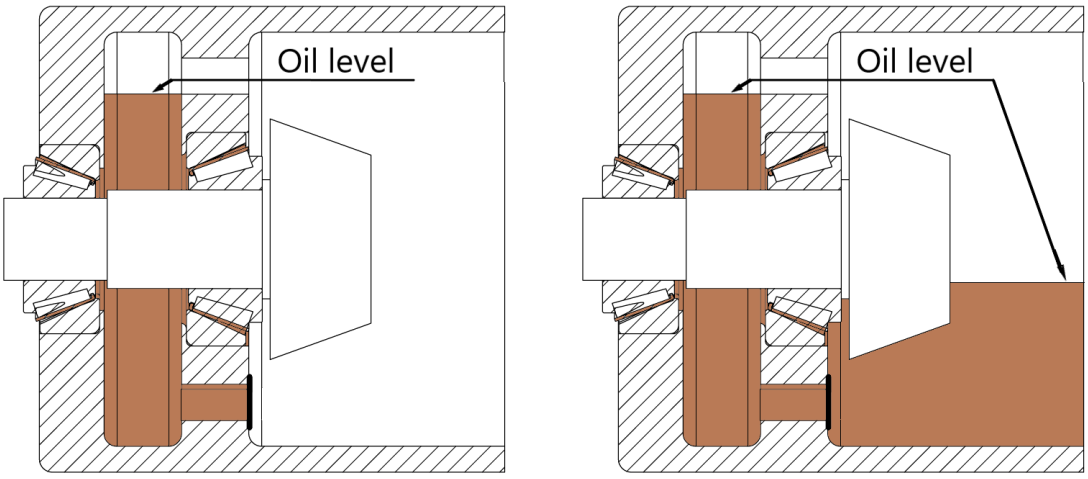


Figure 5.11: Rolling bearings chamber schematic view with a plug.

Then the pinion rolling bearings tests were performed assuring that the rolling bearings are in overflow, therefore they are always immersed in oil in the chamber. This test is divided into two parts, first the rolling bearings losses are measured, and then the pinion and rolling bearings losses, where the rolling bearings continue to be immersed and pinion is bath lubrication, as represented in Figure 5.12. This test allows to perform both the rolling bearings and pinion losses measurements, assuring always the same lubrication conditions at the rolling bearings.



(a) Rolling bearings loss test.

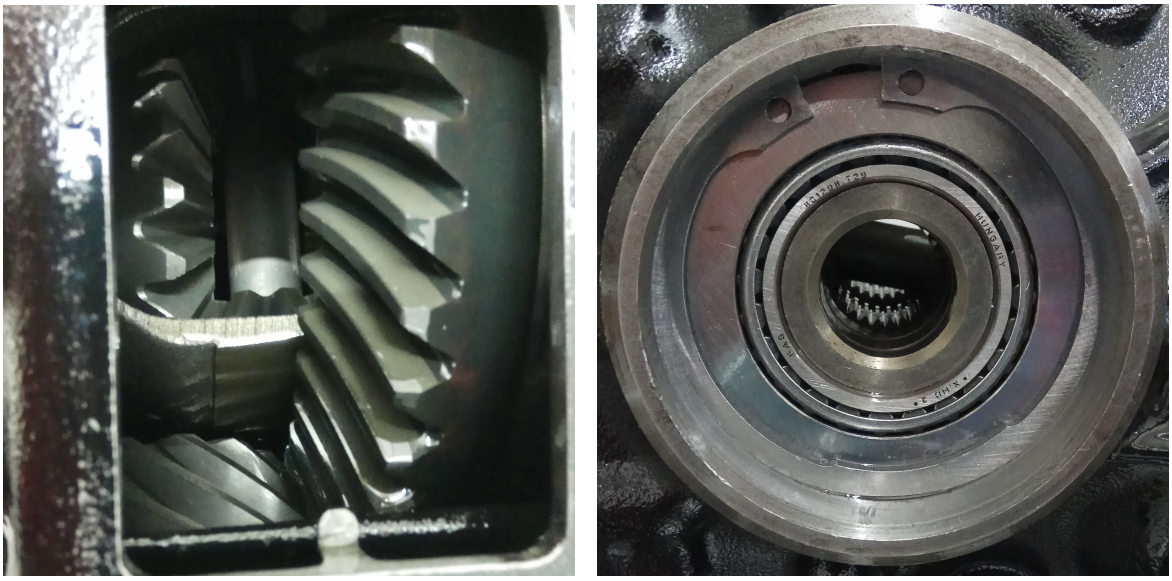
(b) Rolling bearings and churning losses test.

Figure 5.12: Rolling bearings chamber schematic view with a plug and overflow conditions.

During the experimental campaign, it was necessary to perform other tests, presented in Appendix C, that were not successful.

5.3.1 Total Power Loss results without the Output Shaft Seals

First the crown wheel was assembled, so the behaviour that this component has in the differential power loss and the lubrication phenomenon that occur can be observed. The output shafts seals, were not be assembled in order to obtain more specific results, being replaced by plugs that will assure that does not exist any leak and loss.



(a) Top View. **(b)** Side View.

Figure 5.13: Differential with the crown wheel assembled.

The crown churning losses are a difficult to obtain, as it is not possible to run the tests without the rolling bearings that support it. So the results that are presented in this chapter, are relating to the churning losses of the crown wheel and the two rolling bearings that support it.

During this experimental test, it was possible to observe the lubrication methods that occur in the differential. For the crown rolling bearings, lubrication is assured through the oil that is trapped between the rolling bearing and the output shaft seal. This small chamber receives an oil flow that varies depending on the operating conditions.

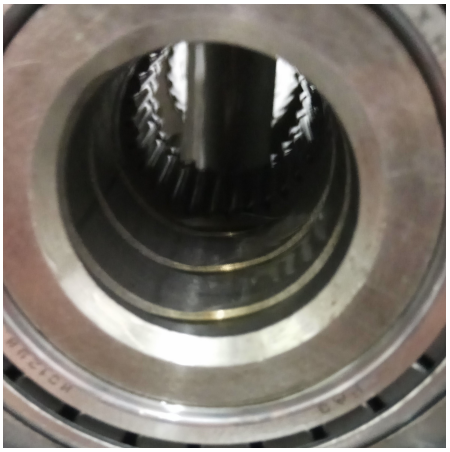
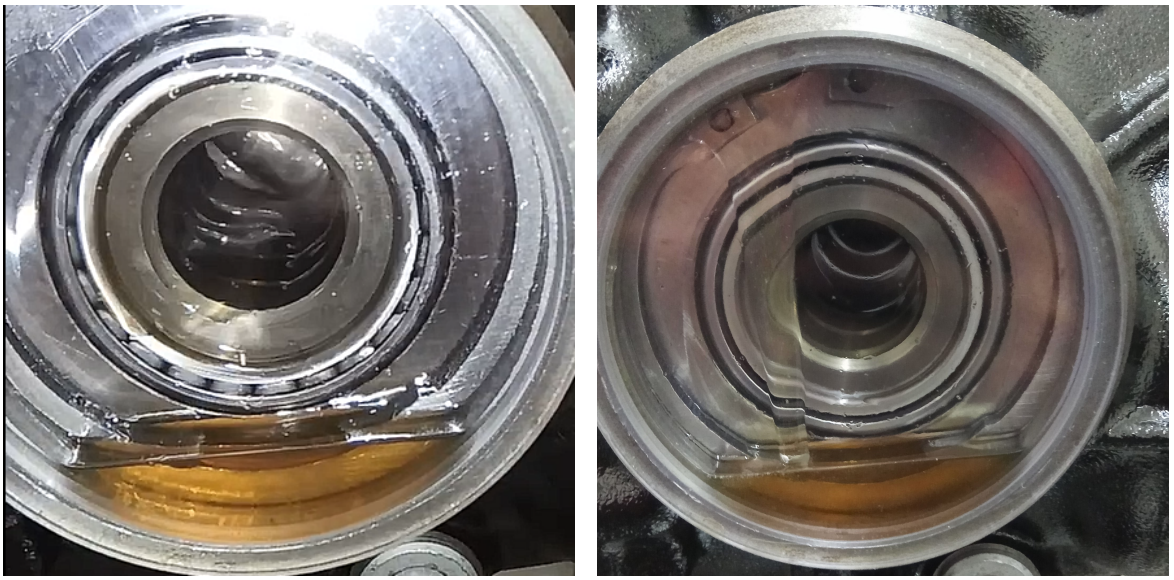


Figure 5.14: Crown wheel spiral path.

For low rotational speeds, the oil reaches the chamber through the centre of the crown wheel, as it is possible to see in Figure 5.15a. This hole was machined with a spiral path, as suggested

in Figure 5.14. This means that for low speeds
there is a good flow of oil to the rolling bearings, but as the speed increases, this flow will decrease. In my opinion, this differential was designed this way, so we have a good lubrication at low speeds, when the gearbox is capable of applying higher torques in the differential. As speeds increase, the drag losses in the rolling bearings start to have a bigger contribution in the losses, so the manufacturer assured a more controlled oil flow.

From approximately a 1000 rpm, the oil flow stops coming from the crown hole, as the spiral path starts to have a bigger influence and a new lubrication mechanism begins. As it is possible to visualize in Table 5.6, at these speeds, it is possible to see the significant oil projection caused by the crown wheel in the oil bath. This oil will be conducted through some channels that exists in the differential walls and will appear in the small chamber between the rolling bearings and output shaft seals. This channel assures an approximately constant oil flow rate to the rolling bearings for higher rotational speeds, as it is possible to see in Figure 5.15b.



(a) Low rotational speed. **(b)** High rotational speed.

Figure 5.15: Lubrication of the crown rolling bearings.

In Table 5.6, it is possible to visualize the variation of the oil path through the operating conditions, caused by the rotation of the crown wheel and the pinion through the oil bath and the influence of the rotational speed and the oil temperature. With the rotational speed decrease, it is possible to observe a more defined oil path and the decrease of projection, although the temperature increase will induce a more “open path”, forming a sort of “oil veil”.

As suggested in Figure 5.16, the no-load torque losses depend essentially on rotational speed and the oil viscosity, which means that also depend on the temperature.

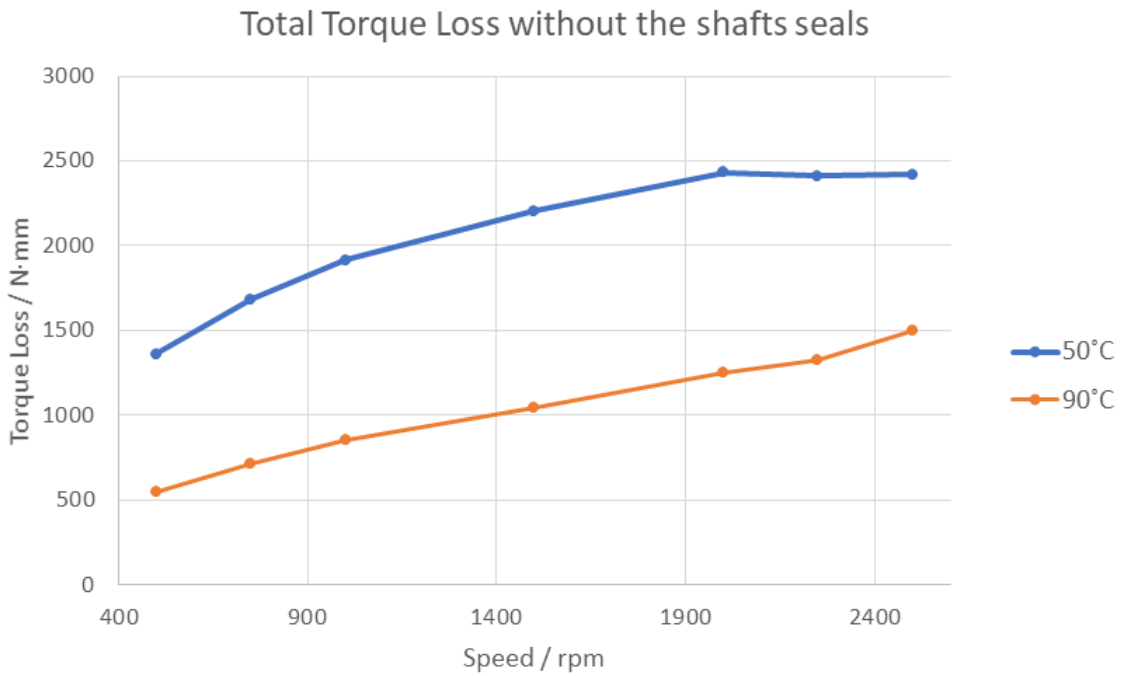
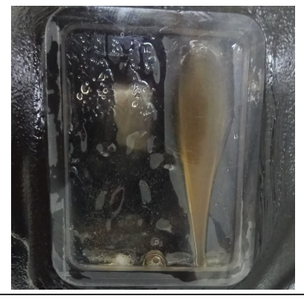
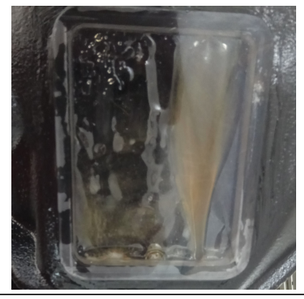
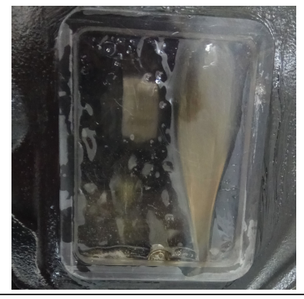
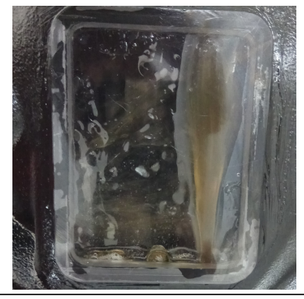
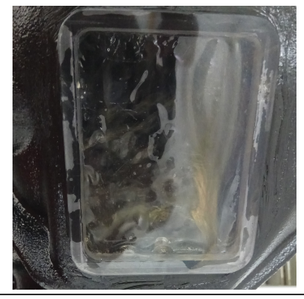
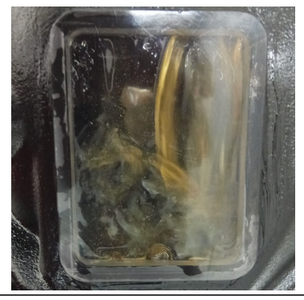
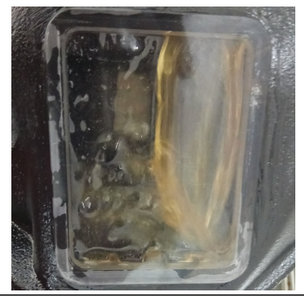
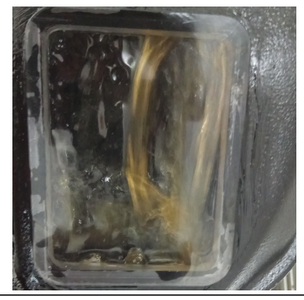
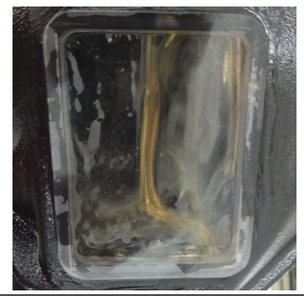
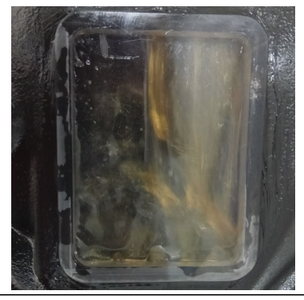
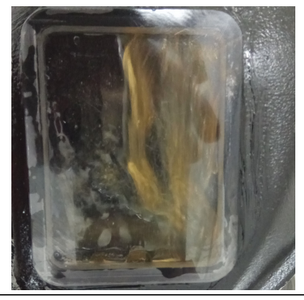
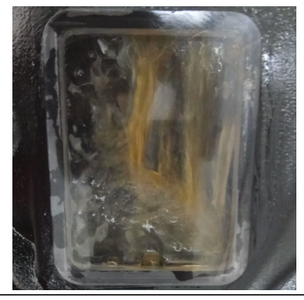
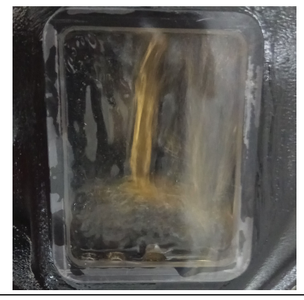
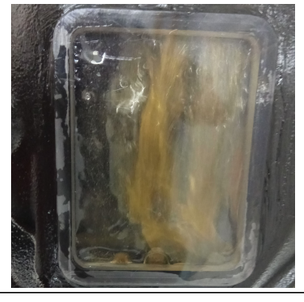
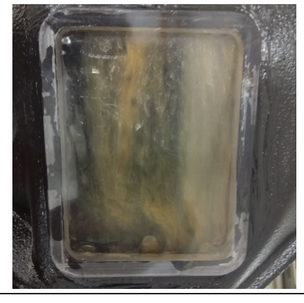
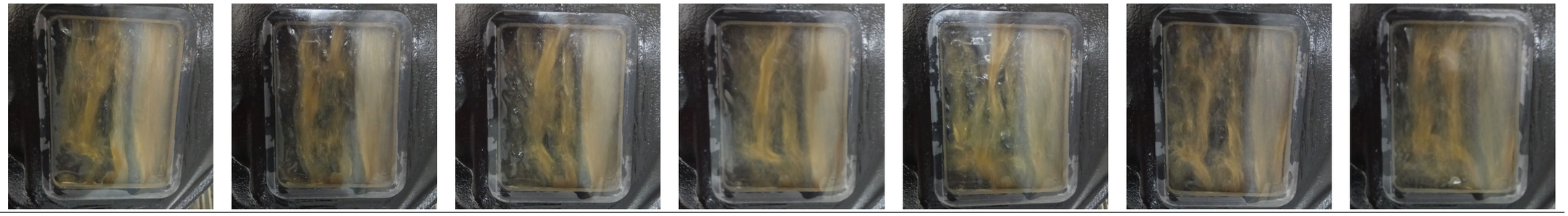
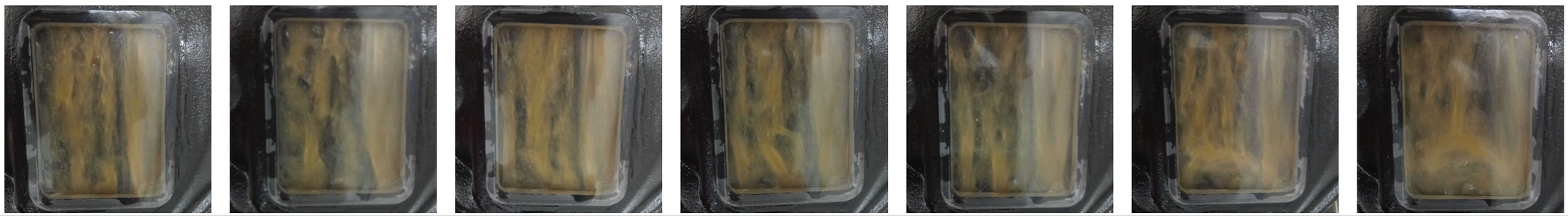


Figure 5.16: Total torque loss without the output shafts seals at 50 and 90 °C.

Table 5.6: Table of figures about the oil path caused by the crown rotation.

Speed rpm	Temperature / °C						
	50	53.3	57.3	62.2	68.5	77.1	90
500							
750							
1000							
1500							

Speed rpm	Temperature / °C						
	50	53.3	57.3	62.2	68.5	77.1	90
2000							
2250							
2500							

5.3.2 Pinion and Rolling Bearings Power Loss results

Then, it was necessary to evaluate the pinion power losses caused by the drag between the oil and pinion surfaces. Because it is not possible to obtain just the churning losses, the rolling bearings and seal losses will be measured, as expressed in equation 5.10.

In order to perform this experiment, the oil level in the differential was set to the level recommended by the differential manufacturer and the crown wheel was removed. This way, it was possible to assure that the rolling bearings lubrication was adequate and verify the increase in the power losses due to the pinion churning losses. The pinion rolling bearings are subjected to a preload that provide a starting torque of 0.75 N·m.

The results from these tests are presented Figures 5.17 and 5.18. In these charts, it is possible not only to visualize the obtained results, but also to compare with the previous results, the total torque losses.

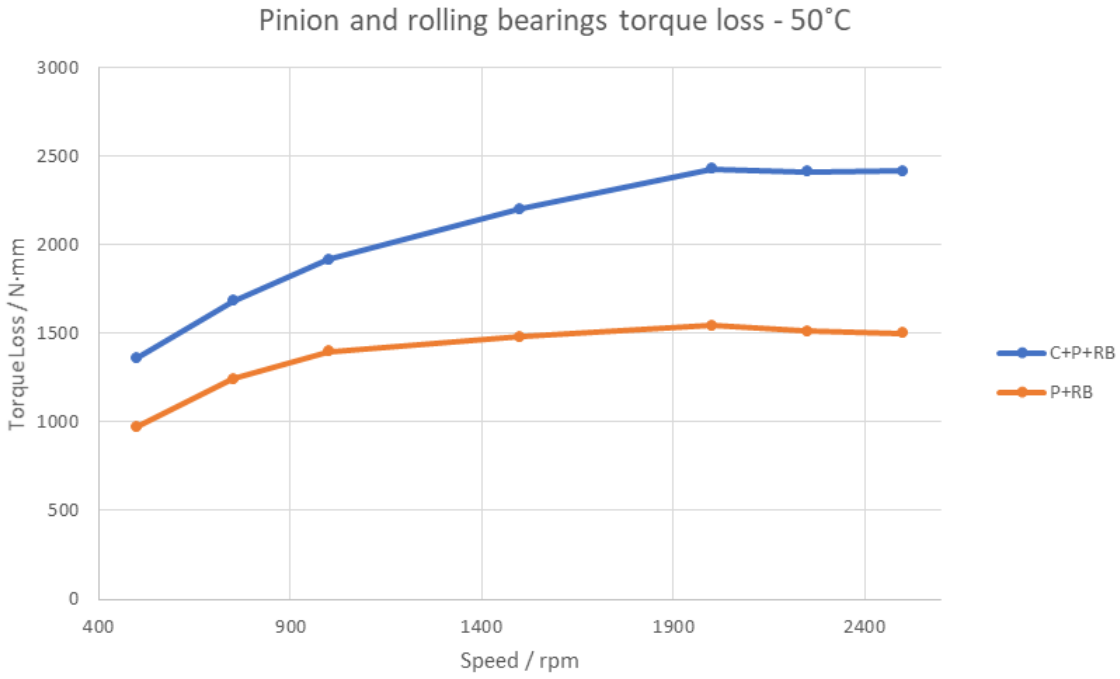


Figure 5.17: Pinion and rolling bearings results at 50 °C.

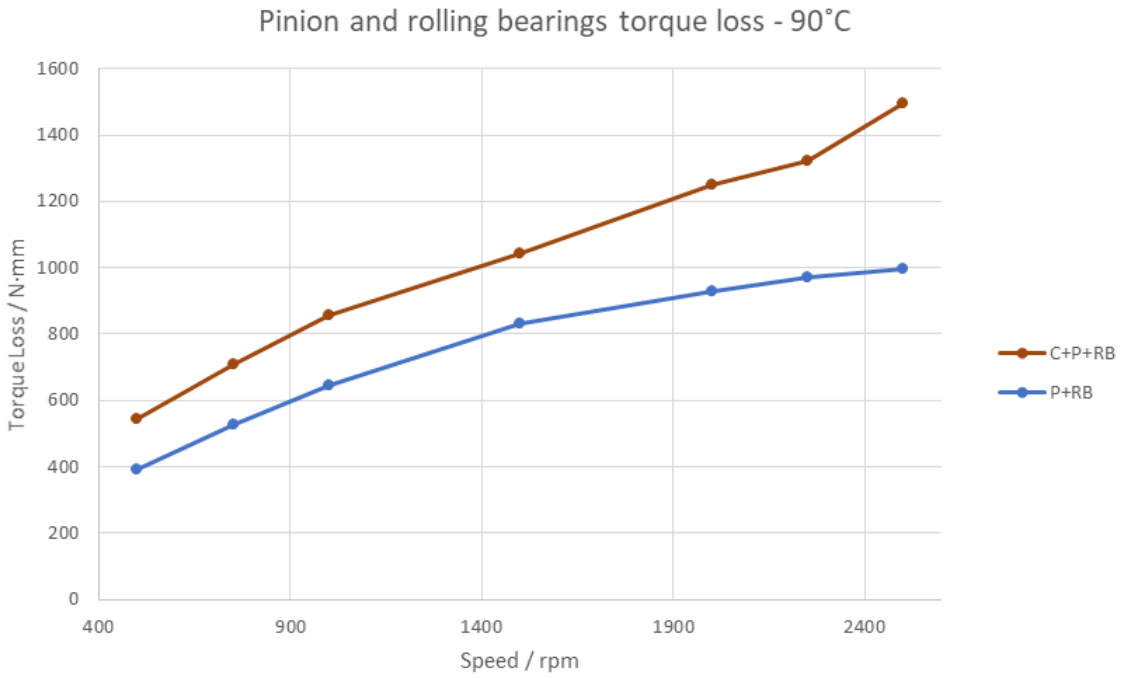


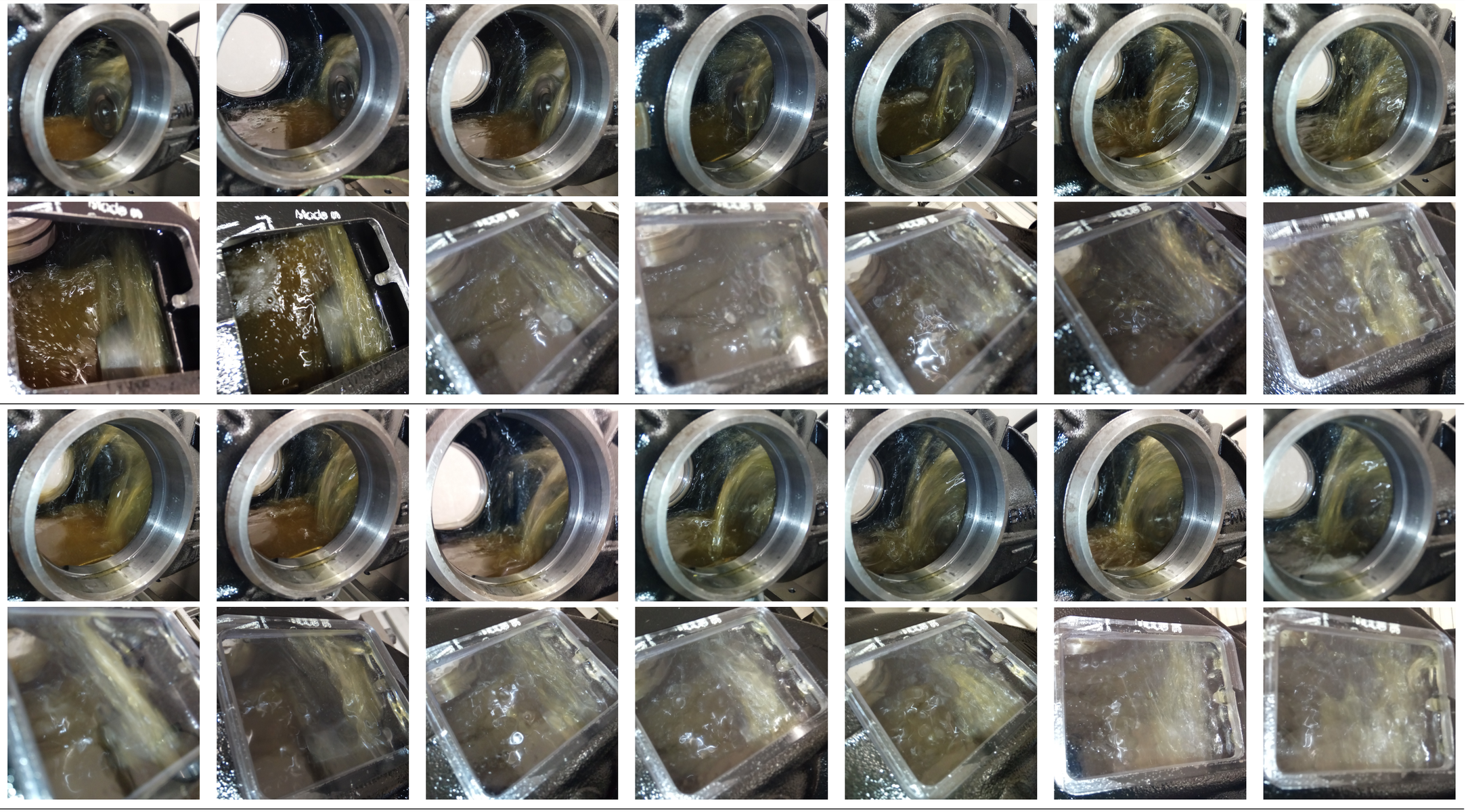
Figure 5.18: Pinion and rolling bearings results at 90 °C.

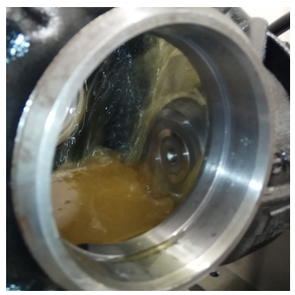
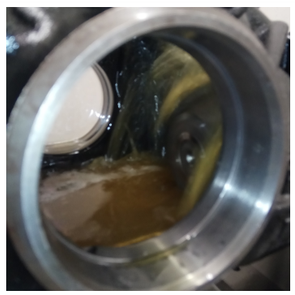
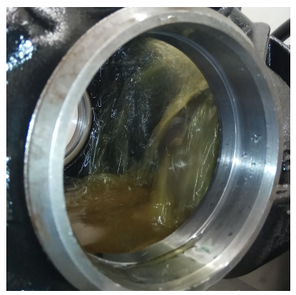
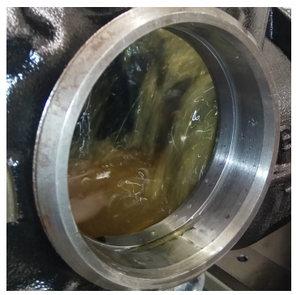
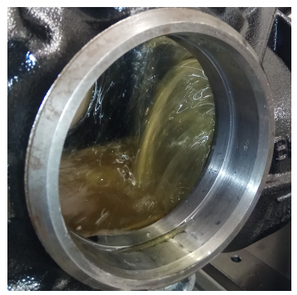
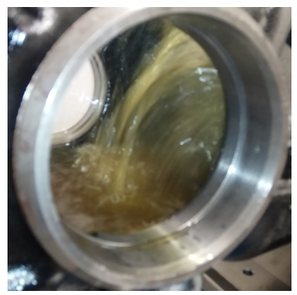
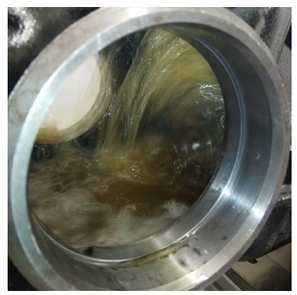
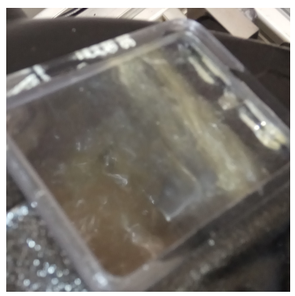
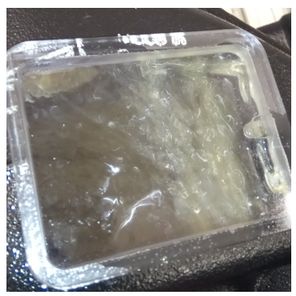
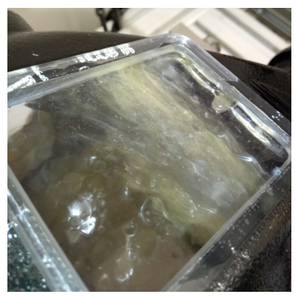
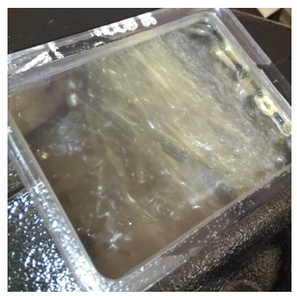
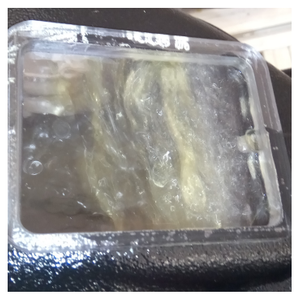
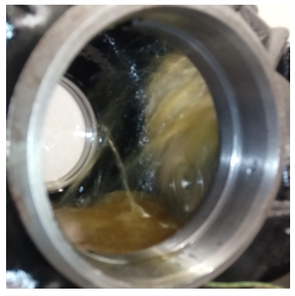
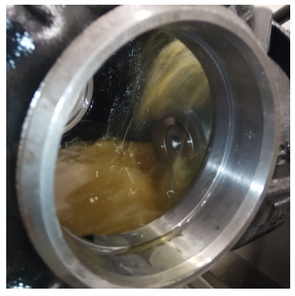
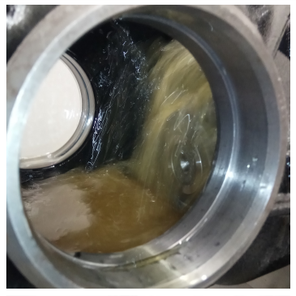
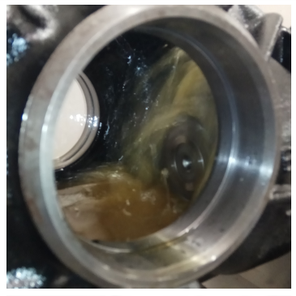
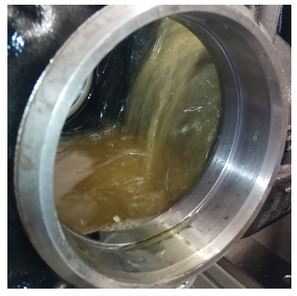
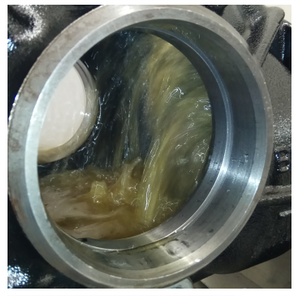
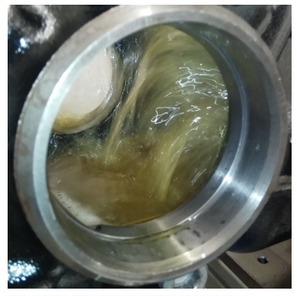
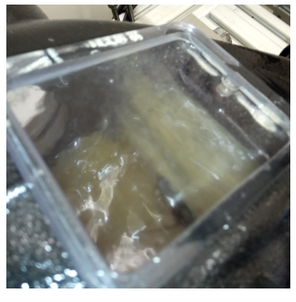
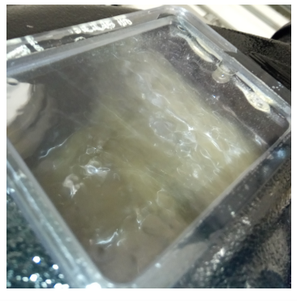
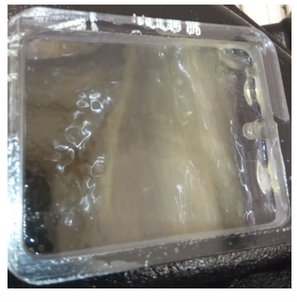
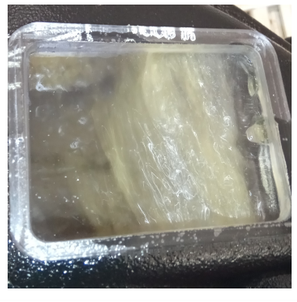
In order to understand the churning losses, some pictures were taken during the experiments and presented in Table 5.7, as it was done to the crown wheel churning. With this information, the idea is to find a pattern between the different conditions of operation.

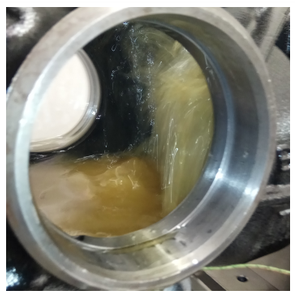
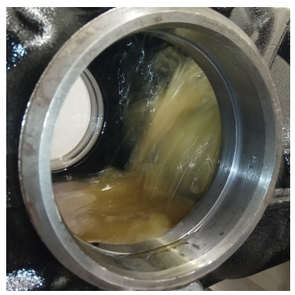
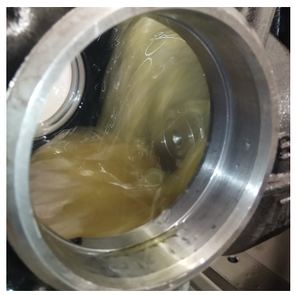
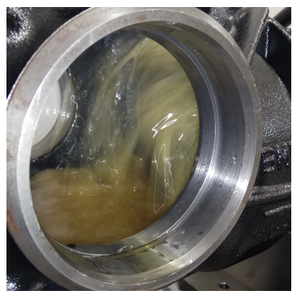
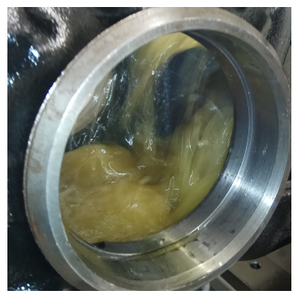
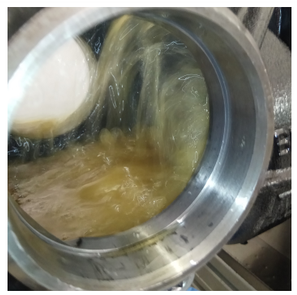
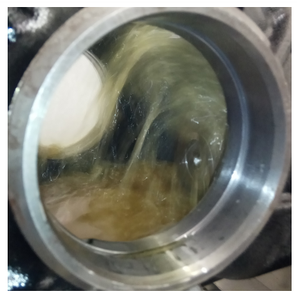
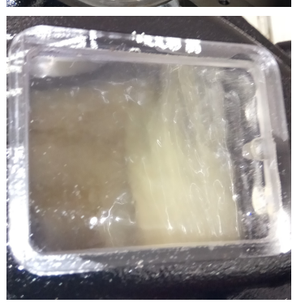
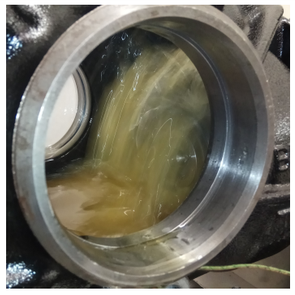
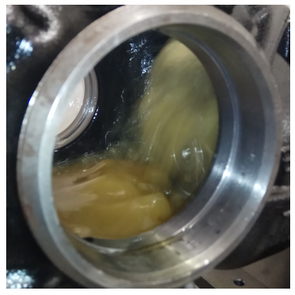
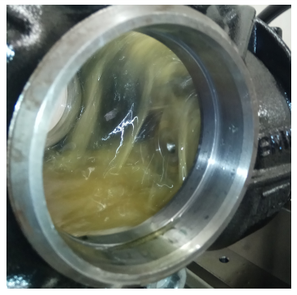
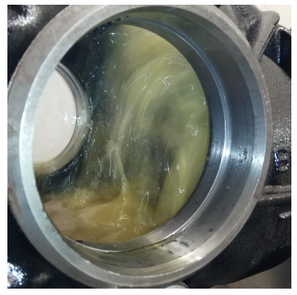
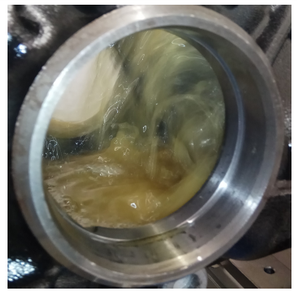
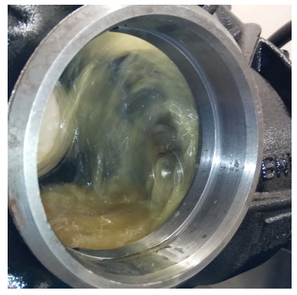
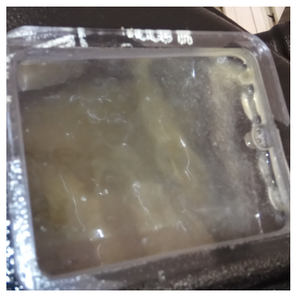
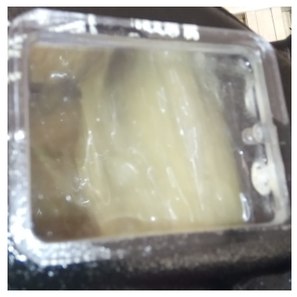
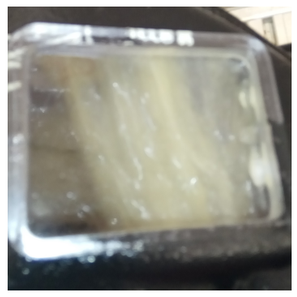
This test was also performed with different starting torques, such as 0.75, 1.9 and 3 N·m. This values were measured using an dynamometer, that measures the necessary torque to iniciate the movement of the pinion shaft. Where it will be possible to verify the influence of this parameter. The obtained results are presented in Figures 5.19 and 5.20 and the remaining temperatures can be observed in Appendix A.2.

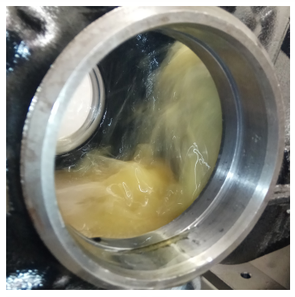
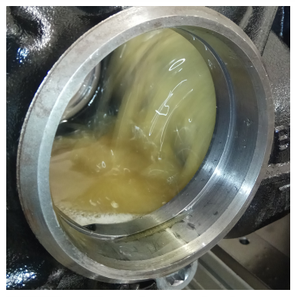
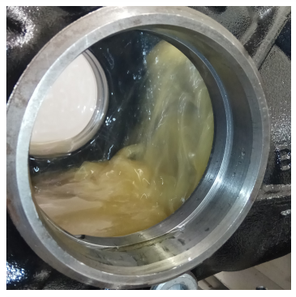
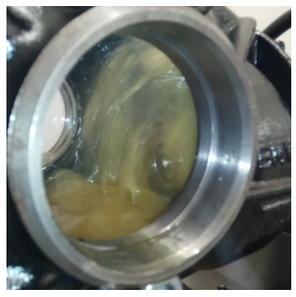
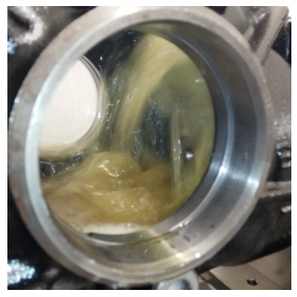
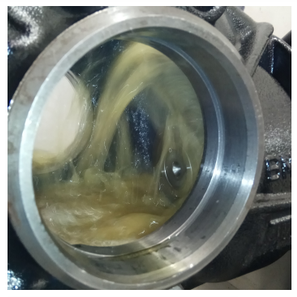
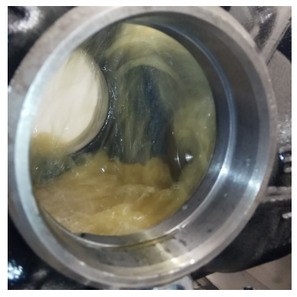
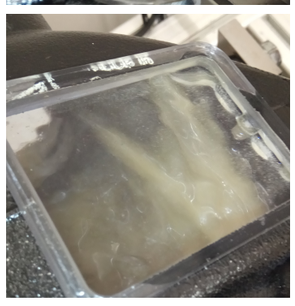
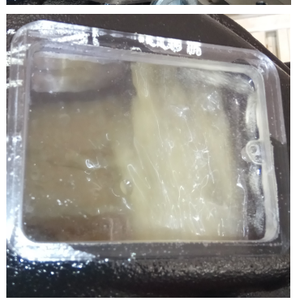
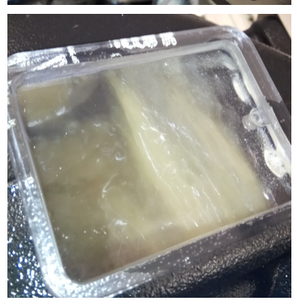
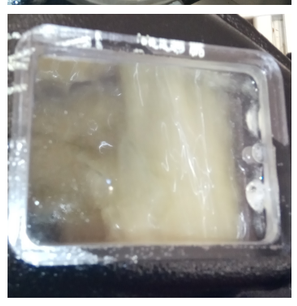
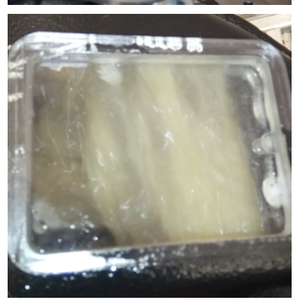
As it was expected, the starting torque increase will induce a higher torque loss in the rolling bearings, although it was also possible to conclude that this torque difference tends to decrease as the starting torque increases.

Table 5.7: Table of figures about the oil path caused by the pinion rotation.

Speed rpm	Temperature / °C						
	50	53.3	57.3	62.2	68.5	77.1	90
500							
750							

Speed rpm	Temperature / °C						
	50	53.3	57.3	62.2	68.5	77.1	90
1000							
							
1500							
							

Speed rpm	Temperature / °C						
	50	53.3	57.3	62.2	68.5	77.1	90
2000							
							
2250							
							

Speed rpm	Temperature / °C						
	50	53.3	57.3	62.2	68.5	77.1	90
2500							
							

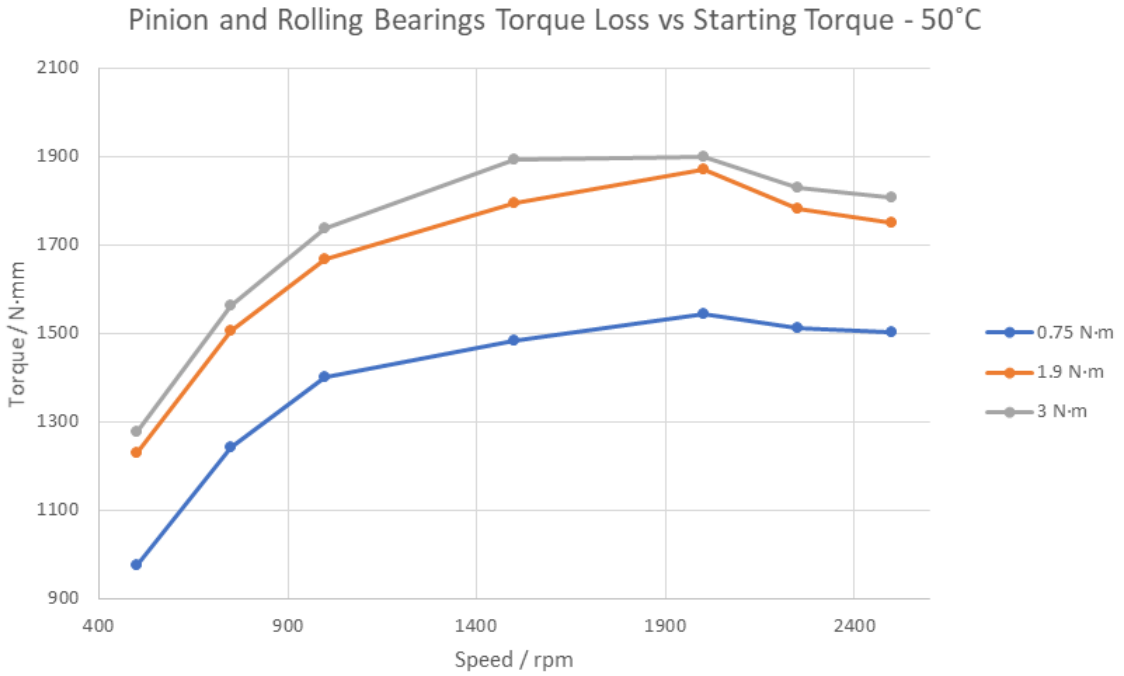


Figure 5.19: Pinion and rolling bearings torque loss comparison between different starting torque at 50 °C.

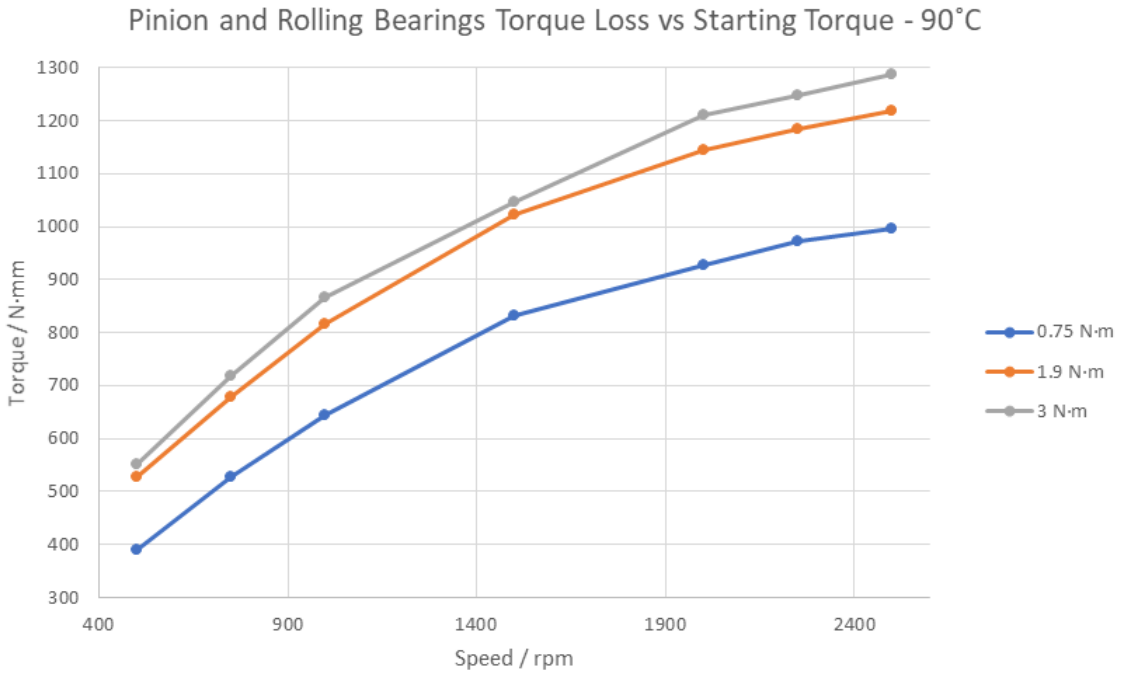


Figure 5.20: Pinion and rolling bearings torque loss comparison between different starting torque at 90 °C.

5.3.3 Pinion Rolling Bearings Power Loss results for different Oil Flow Rates

This test consists in finding the ideal oil flow rate for each condition of speed and temperature, in order to find the minimum power loss that can be obtained using oil circulation lubrication. This test will help understanding the influence of the flow rate through the rolling bearings, as it will be done for many different flow rates. In Figures 5.21 and 5.22, it is possible to verify the obtained results, where it is presented the minimum values of torque loss for each operating condition.

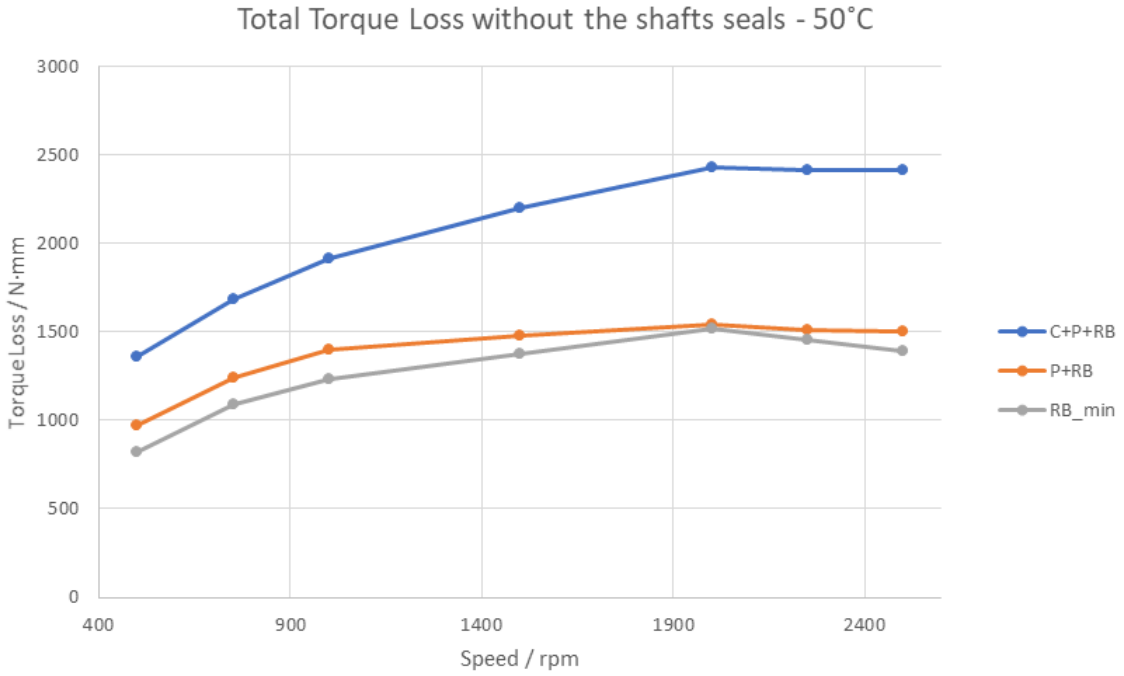


Figure 5.21: Rolling bearings minimum results at 50 °C.

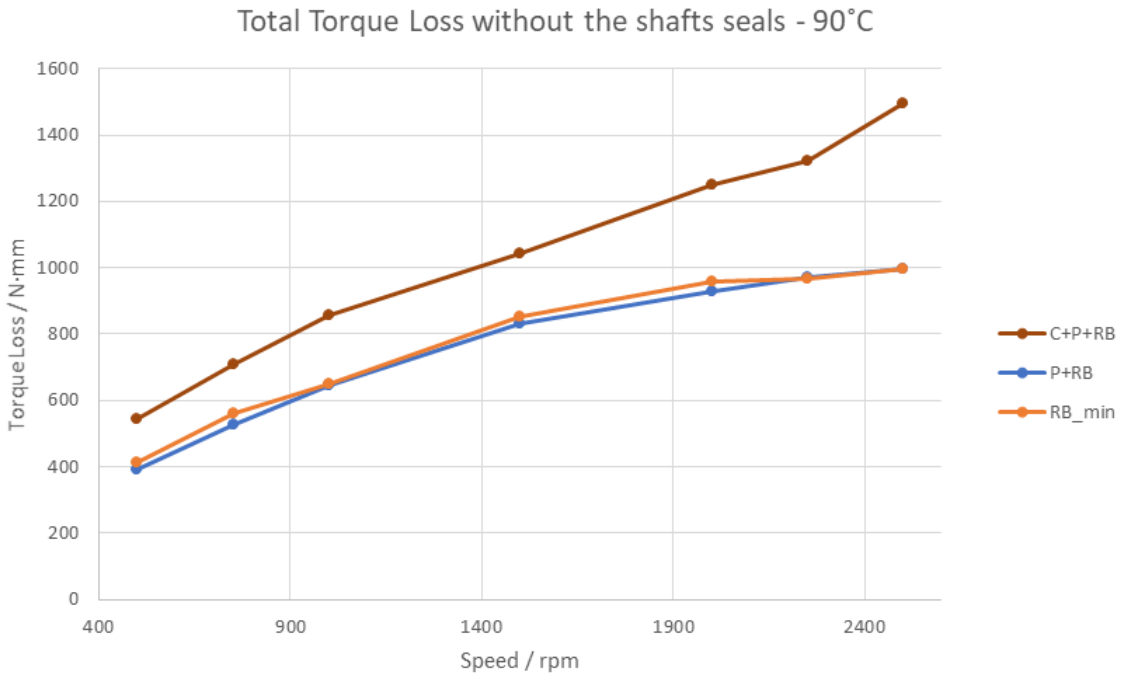


Figure 5.22: Rolling bearings minimum results at 90 °C.

In appendix A.3, all of the obtained results are presented, where a more in depth analysis about the influence of the oil flow rate in the rolling bearings torque loss can be made. With this study it was possible to conclude that each condition has a different necessity of lubrication and it is barely impossible to simulate the oil bath condition with the oil circulation system, even ensuring the same oil level.

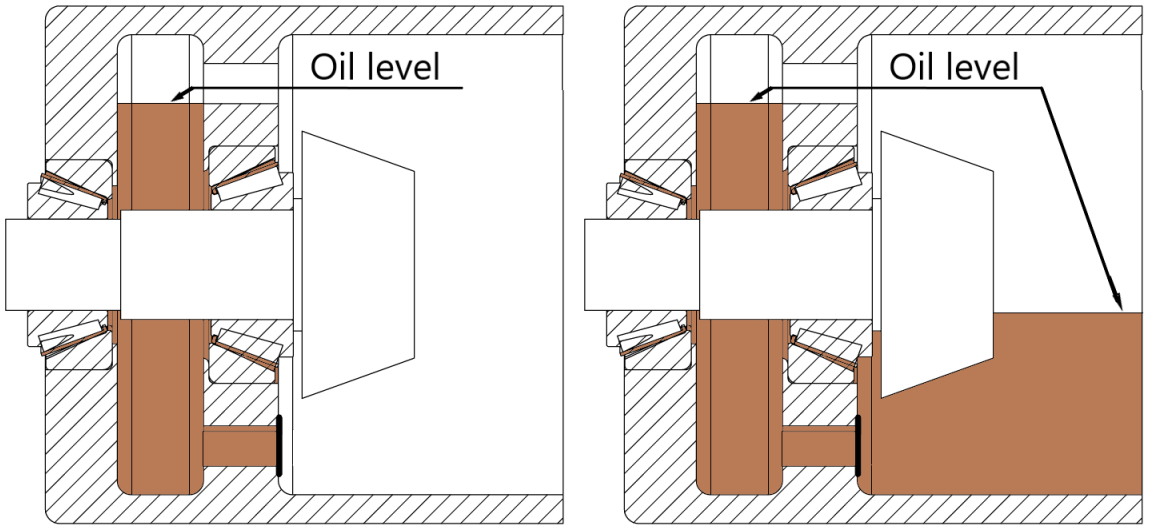
5.3.4 Pinion Power Loss results with Rolling Bearings in overflow

In this test, the idea is to assure the same lubrication conditions to the rolling bearings, instead of trying to simulate the oil bath using oil circulation lubrication. This test consists in assure that oil level inside the rolling bearing chamber is always above of the rolling bearings. The oil will still be provided from the oil pump and the crown wheel had to be removed. The main reason to choose this lubrication characteristics is due to the lower possible influence in the lubrication conditions that can be assured, when the oil bath is added in the other side of the rolling bearings. This test will provide results were it is possible to remove the pinion churning losses.

This test is divided in 2 parts, first we have to perform a test where we try to find the power loss of the rolling bearings in overflow. At 500 rpm, the oil flow rate will be set, ensuring that the oil level is above the rolling bearings. The oil flow rate can not be corrected as the speed increases, because the speed increases the pressure in

the tube, giving a wrong information of the oil level. A schematic view of this test can be observed in Figure 5.23a.

The second part consist in repeat the previous procedure, but now the pinion is also immersed in oil, as represented in Figure 5.23b. The level plug will be open, in order to assure a correct oil level in the pinion.



(a) Rolling bearings loss test.

(b) Rolling bearings and churning losses test.

Figure 5.23: Rolling bearings chamber schematic view with a plug

The test was repeated and the obtained results can be seen in Figure 5.24 and 5.25, where the rolling bearing torque loss was already subtracted and the pinion churning losses were obtained.

It is possible to concluded that, the pinion churning losses have a small influence in the total power loss. In Figure 5.25, it is possible to verify that the pinon torque loss assumes negative values at some points. As we are trying to measure such small values, any error in the measurements can induce negatives values.

During the tests, it was noticed that the manufacturer oil level requirements in the differential were not completely fulfilled. The oil level plug was not capable to assure the right flow rate and the oil level slightly increased.

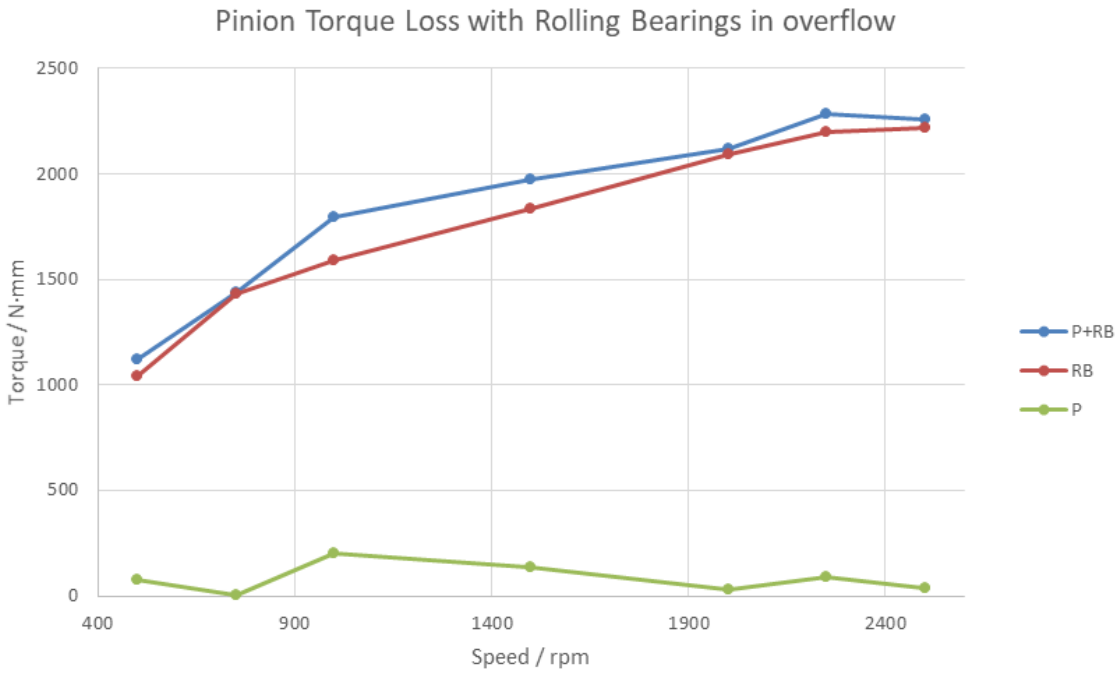


Figure 5.24: Pinion torque loss with rolling bearings in overflow for the first test at 50°C.

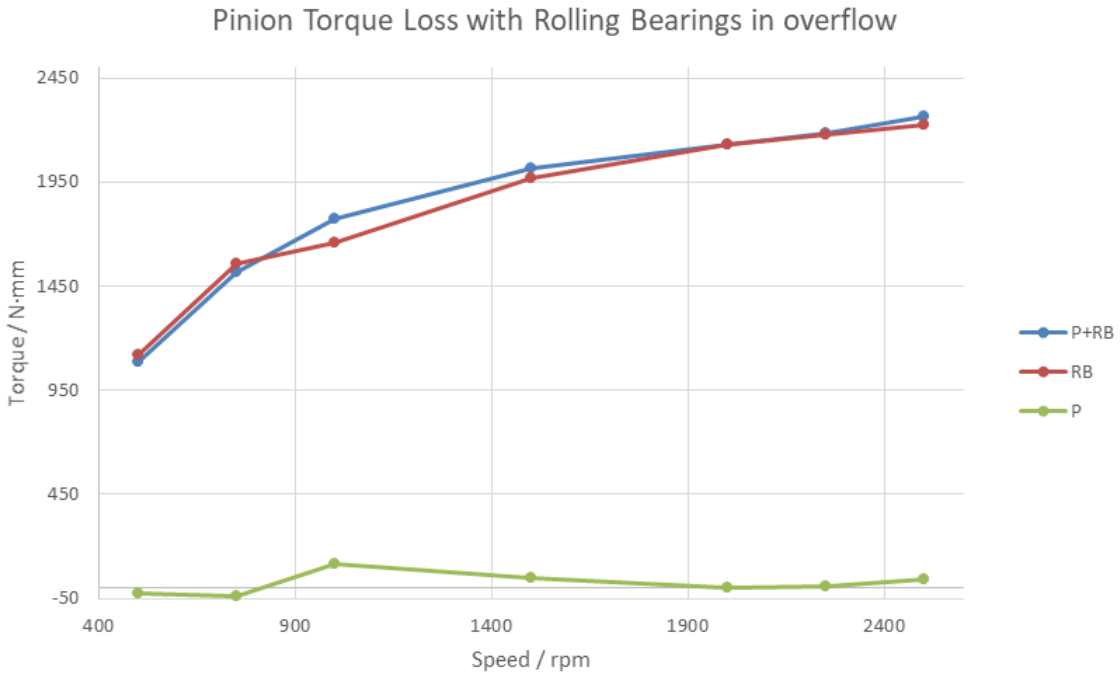


Figure 5.25: Pinion torque loss with rolling bearings in overflow for the second test at 50°C.

With this results, it is possible to conclude that the contribution of pinion churning loss is too low, therefore the test rig does not have such sensibility to provide a good measurement.

6 Results Analysis

6.1 Oil Characteristics

The main objective of this section is to verify the models truthfulness when compared with the experimental results. This will allows us to have more trust in this models, when it is not possible to have the experimental data.

6.1.1 Viscosity

As observed in Figure 6.1, the models presented in section 3.1.1 are able to predict the viscosity variation with the temperature. Although the difference is very small, the SV-10 test presents better results when compared with the information provided from the lubricant manufacturer.

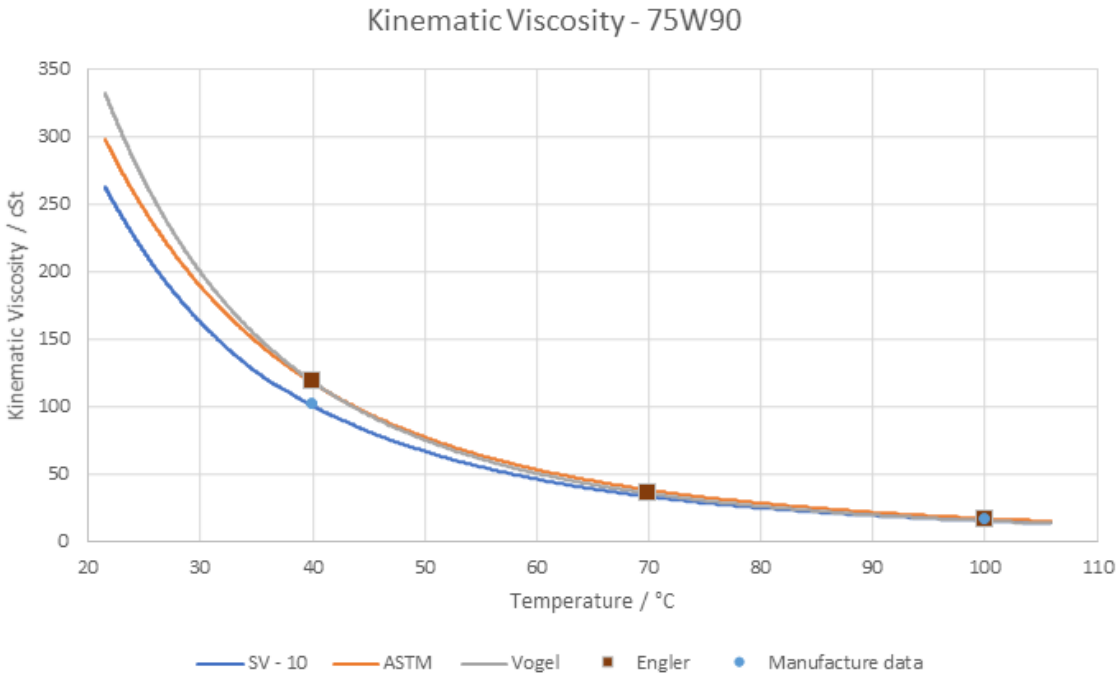


Figure 6.1: Viscosity results comparison with different models.

6.1.2 Density

After analysing Figure 6.2, it is possible to conclude that equation 3.6 presents a good approximation with the experimental results. It is important to notice that

the experimental results have an error of 0.64% when compared with the lubricant specifications.

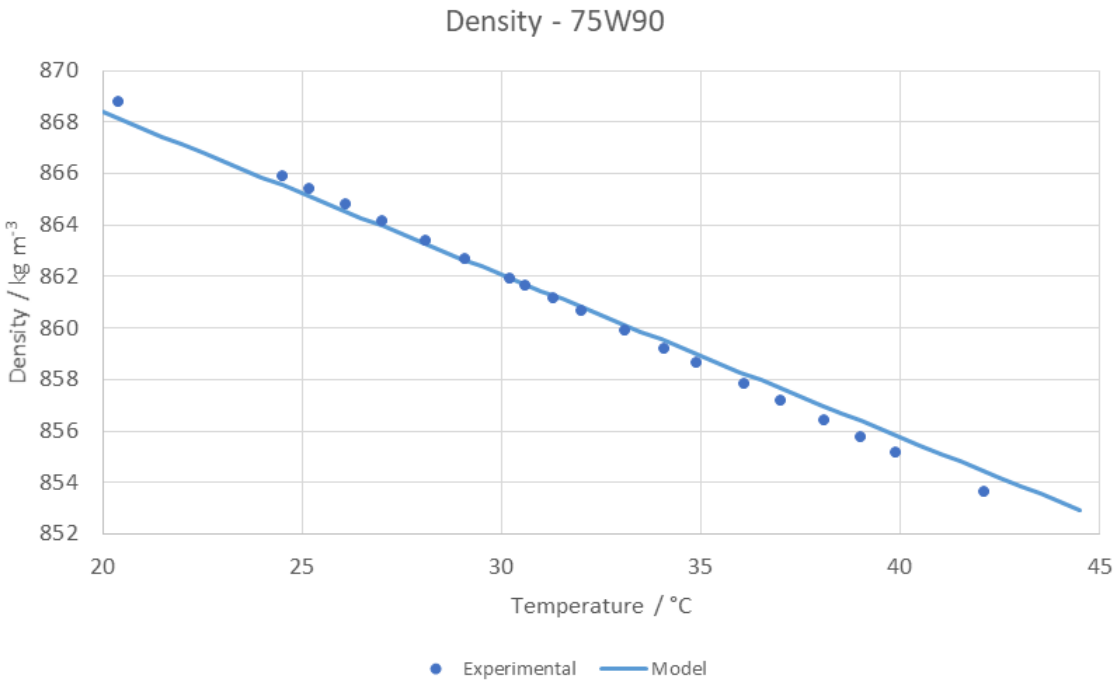


Figure 6.2: Density results comparison with the model.

6.2 Rear Axle Experimental results

The total torque loss can be divided as presented in equation 6.1. As it was not possible to obtain all the results experimentally, the Fossier [1] churning model and Simrit [32] seal model were used.

$$T_{exp} = \overbrace{C_{FS} + RB_c}^{C_{exp}} + \overbrace{P_{FS} + RB_p^{exp} + V_{sim}}^{P_{exp}} \tag{6.1}$$

Where:

- T_{exp} - Total torque loss without the output shaft seals;
- C_{exp} - Crown wheel experimental results;
- P_{exp} - Pinion experimental results;
- C_{FS} - Crown wheel churning loss according to Fossier [1];
- RB_c - Crown wheel rolling bearings loss;

- P_{FS} - Pinion churning loss according to Fossier [1];
- RB_p^{exp} - Pinion rolling bearings experimental loss;
- V_{sim} - Pinion seal loss according to Simrit [32].

In Figure 6.3, it is represented the crown wheel contribution in the total power loss, where it is possible to understand where are the majors problems in terms of efficiency and if possible, propose some more efficient alternatives.

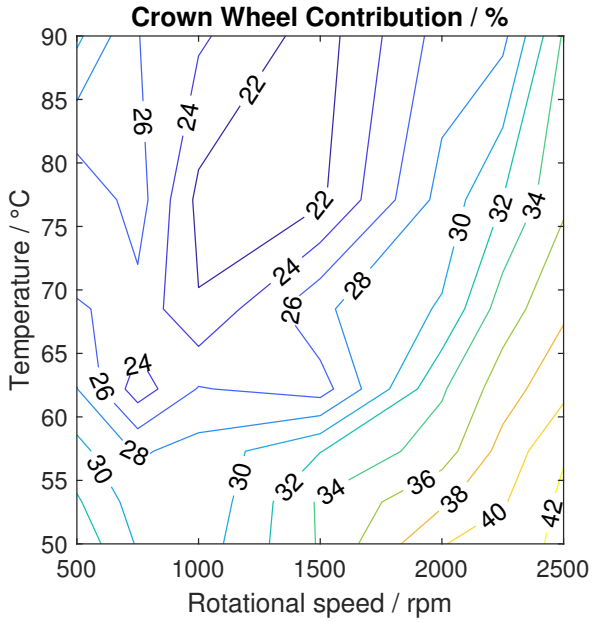


Figure 6.3: Contribution of the crown wheel in the total power loss.

With this information, it is possible to visualize the influence of oil viscosity and speed. As the viscosity and the speed increases the crown wheel churning losses are more considerable, increasing the contribution of the crown wheel in the total power loss.

In average, the crown wheel contributes 31 % of the total power loss. Although its higher dimensions and higher churning losses, the rolling bearings have a very low preload when compared to the pinion rolling bearings. This means that the pinion rolling bearings are main responsible for no-load power loss of the differential.

6.2.1 Pinion

In Figure 6.4, it can be observed the pinion torque loss results variation with the speed and temperature, that includes the pinion churning, rolling bearings and

seal losses. As expected, the increase of speed and decrease of the oil temperature will increase the torque losses.

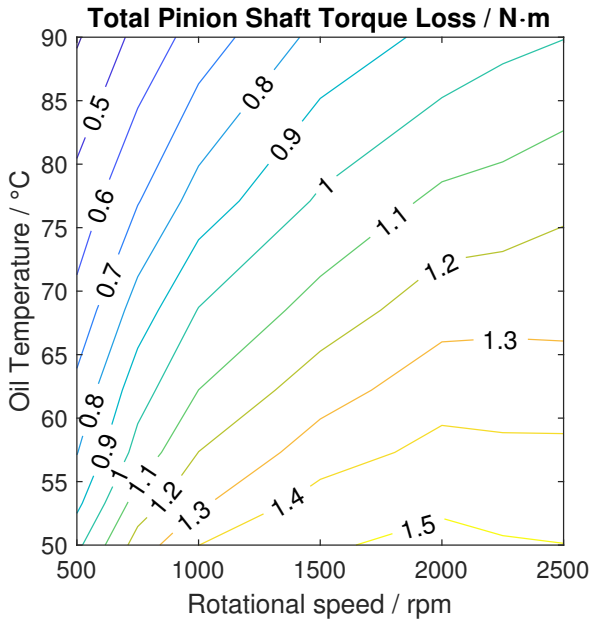


Figure 6.4: Pinion torque loss variation with speed and temperature.

In order to perform a more detailed analyses, in Figures 6.5 and 6.6 it is possible to visualise the pinion experimental results, that includes the pinion and rolling bearings and the minimum rolling bearings torque loss results, and compared with the models. Only the 50 °C and 90 °C are represented, and the remaining temperatures can be found in Appendix A.4.1. The Fossier [1] model is represented and is also summed up to the minimum rolling bearings loss and Simrit [32] model, which is equivalent to the pinion losses.

With this results, it is possible to conclude that the rolling bearings represents the major loss in the pinion losses. This can be explained by the high preload that this rolling bearings are subjected to. The churning and seal losses only represents a small portion of the pinion losses (approximately 2.7 %), explaining the difficulty of obtain this results experimentally.

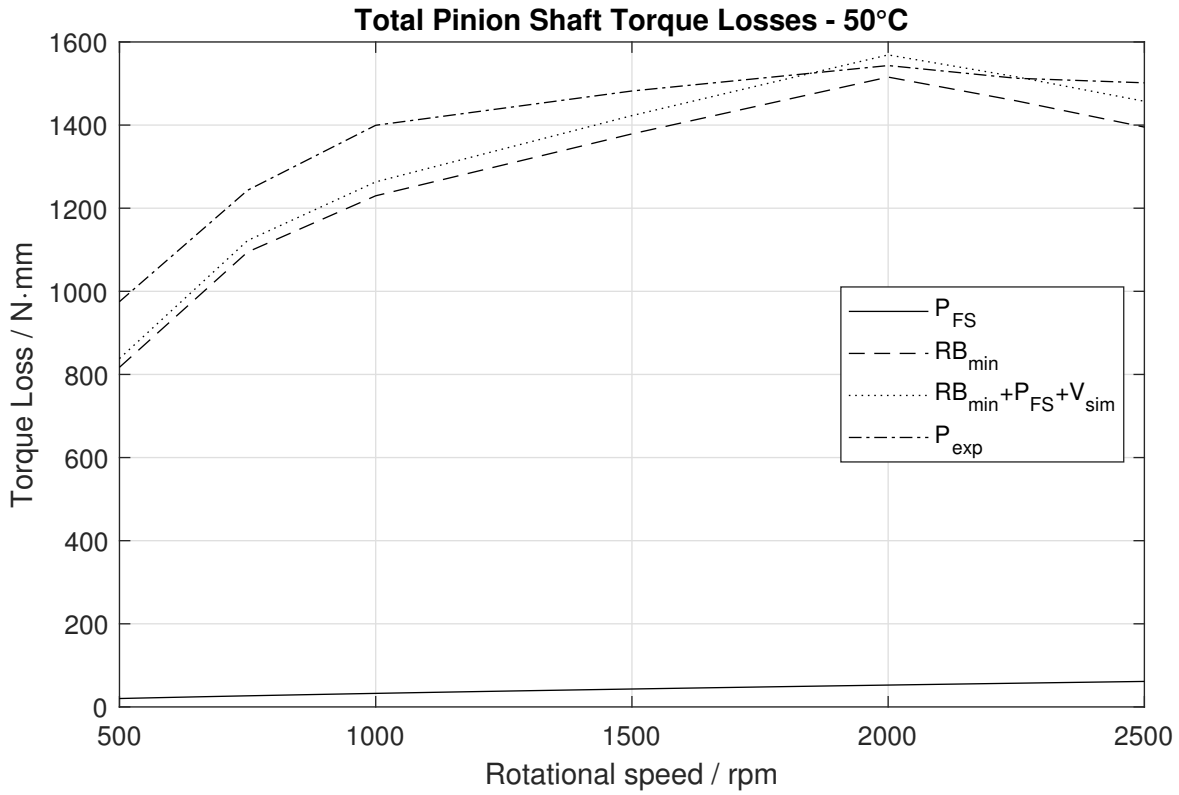


Figure 6.5: Pinion torque losses comparison at 50 °C.

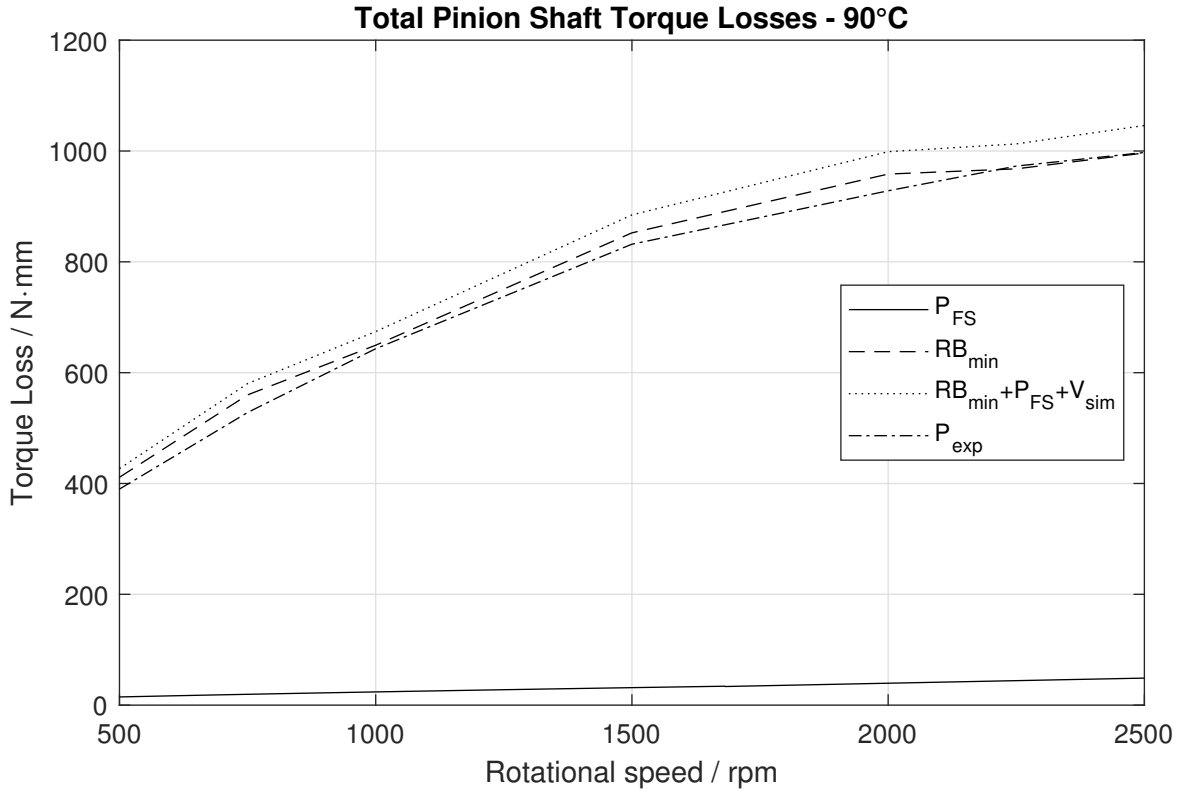
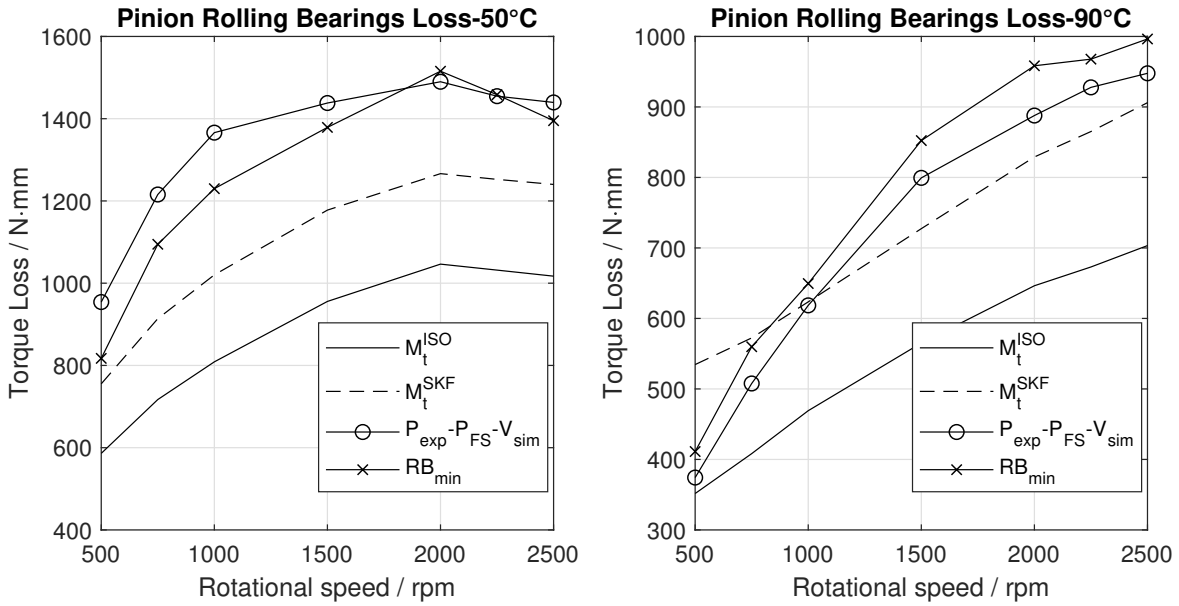


Figure 6.6: Pinion torque losses comparison at 90 °C.

In Figure 6.7, it can be visualised a comparison between the experimental results and the models presented in the literature. This experimental results were obtained using a starting torque of 0.75 N·m. As it is not possible to measure the preload that the pinion rolling bearings are subjected to, it was assumed a value of 1000 N. Which means that only the results tendency can be compared.



(a) Pinion rolling bearings torque loss at 50 °C.

(b) Pinion rolling bearings torque loss at 90 °C.

Figure 6.7: Pinion rolling bearings torque loss models comparison with the experimental results.

From this results, it is possible to conclude that none of the presented models represents a exact same tendency like the experimental results. For the pinion rolling bearings results, it can be verified that the torque loss increases up to a defined limit, where it remains constant as the speed increases. This effect can be explained by the temperature increase in the rolling bearings for higher rotational speeds, which let to the viscosity decrease, therefore decreasing the torque loss. It should be noticed that the torque loss experimental values can not be compared with the models, as the rolling bearing preload is not known and it was assumed a 1000 N in the models and the measured rolling bearings temperature was considered in the models, in order to a more exact comparison.

With the obtained results, it was possible to modulate equation 6.2, which can represent the torque loss of the pinion rolling bearings for the different speeds and oil viscosities. Figure 6.8 represents a point cloud, where the presented model can be compared with the experimental results. The model can be observed in Figure 6.9, where a comparison can be done between the experimental results and the model at a temperature of 77.1 °C for different starting torques. All the remaining charts can be visualised in Appendix A.4.1.

$$M = 12.52 \cdot (\eta \cdot w \cdot R_m \cdot T^2)^{0.19} \cdot (M_{st} + 4.24)^{0.81} \cdot Re^{-0.43} \cdot Fr^{0.35} \quad (6.2)$$

Where:

- $\boldsymbol{M}$ - Rolling bearing frictional moment [N·m];
- $\boldsymbol{\eta}$ - Dynamic viscosity of the lubricant [N s m^{-2}];
- $\boldsymbol{R_m}$ - Rolling bearings mean radius [m];
- $\boldsymbol{T}$ - Rolling bearing width [m];
- $\boldsymbol{M_{st}}$ - Rolling bearings starting torque [N·m];
- $\boldsymbol{Re}$ - Reynolds number;
- $\boldsymbol{Fr}$ - Froude number.

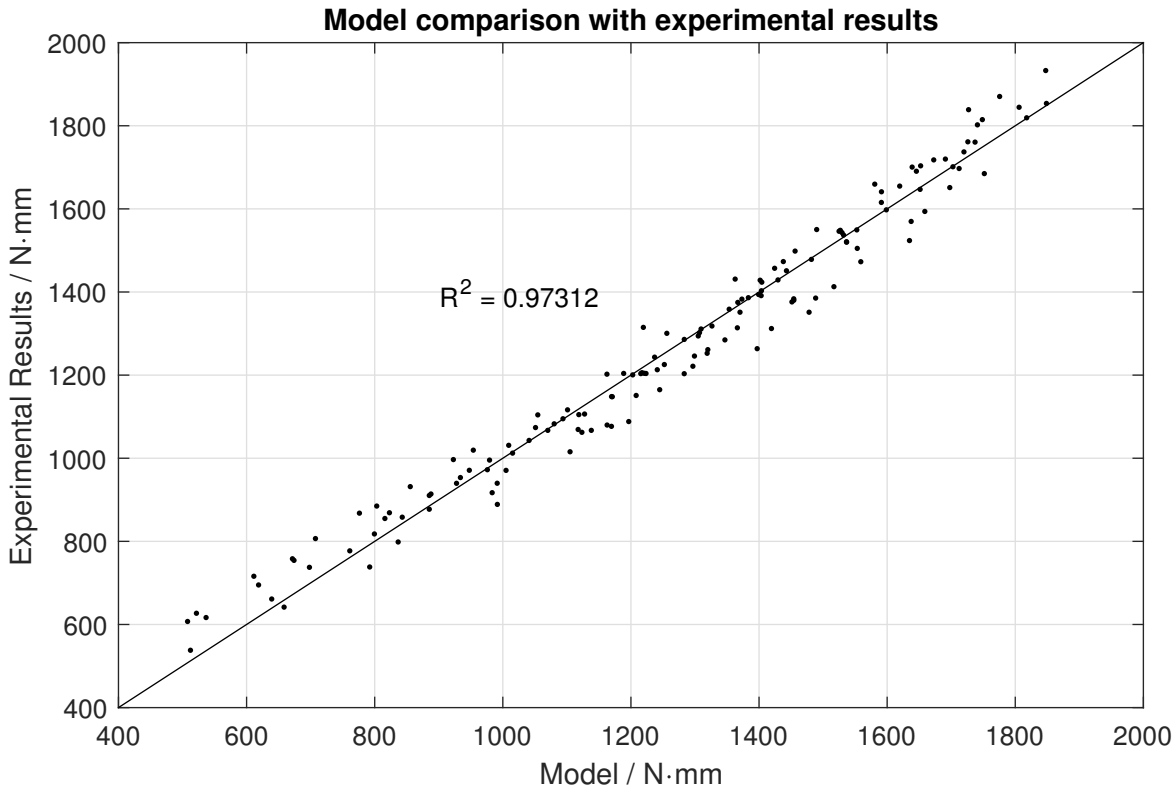
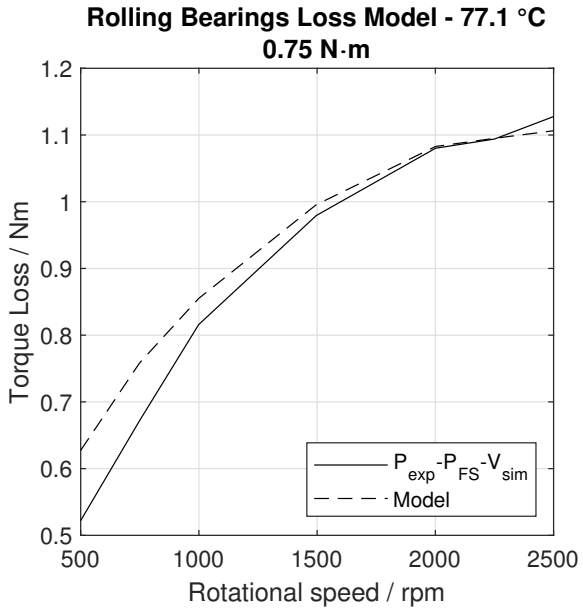
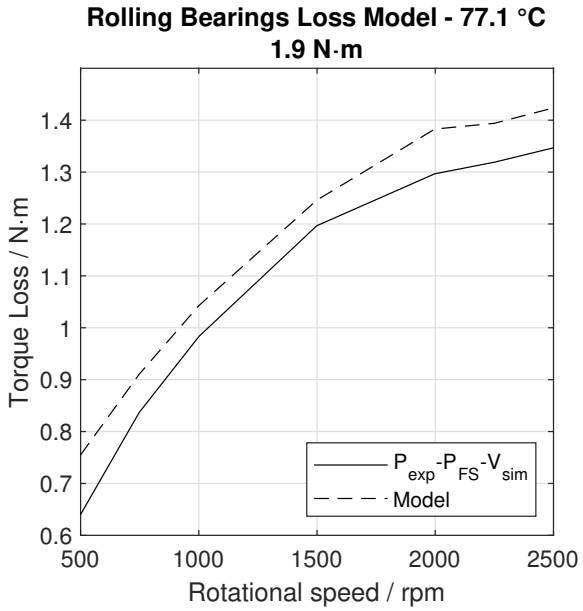


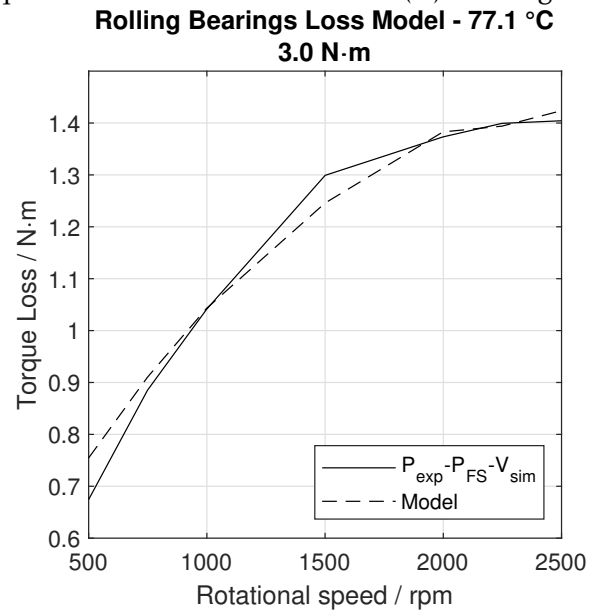
Figure 6.8: Model comparison with experimental results.



(a) Starting torque of 0.75 N·m.



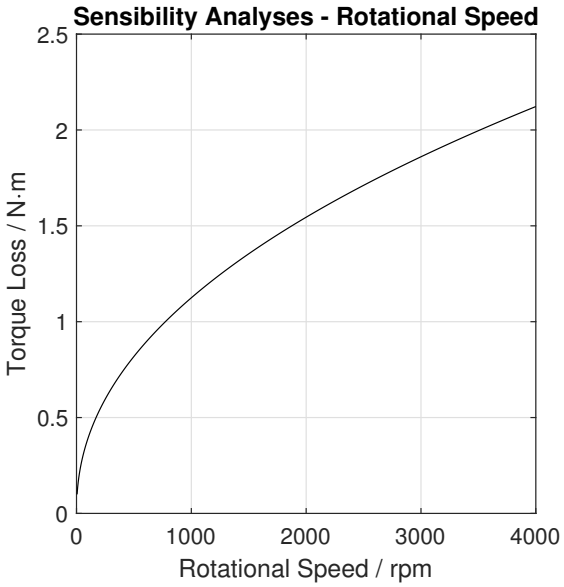
(b) Starting torque of 1.9 N·m.



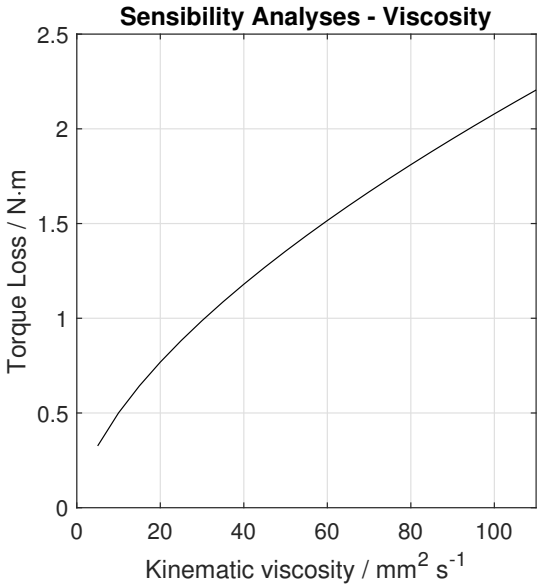
(c) Starting torque of 3 N·m.

Figure 6.9: Rolling bearing torque loss models comparison with the experimental results at 77.1 °C.

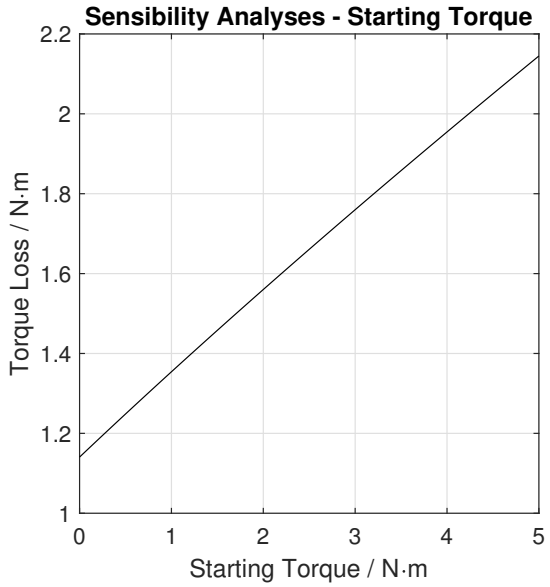
In order to validate the presented model, a sensibility analyses was done for the different variables of the model. In Figure 6.10, it is possible to analyse the variation of the respective variable and to analyse the influence of the rolling bearings, some of them were choose and presented in Table 6.1. To obtain the representations, it was considered the following parameters constants, except the variable that is being analysed: n = 500 rpm; v = 50 Cst; M_{st} = 1 N·m; Rm = 28.18 mm; T = 29.37 mm; ρ = 866 kg m^{-3}; g = 9.81 m s^{-1}.



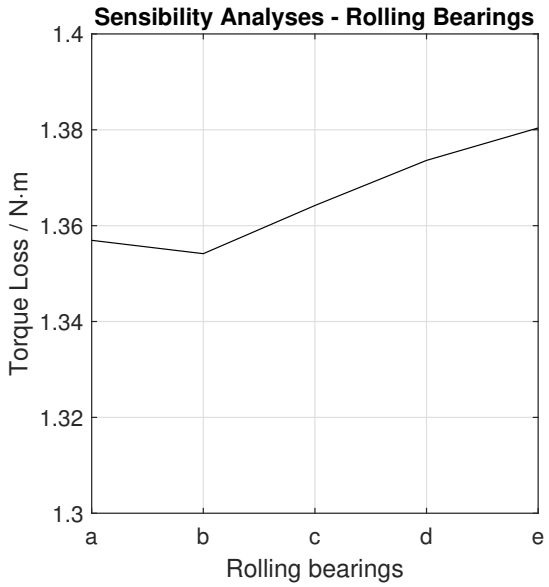
(a) Rotational speed influence.



(b) Oil viscosity influence.



(c) Starting torque influence.



(d) Rolling bearings influence.

Figure 6.10: Model sensibility analyses.

Symbol	Reference	D / mm	d / mm	T / mm
a	HM 88649/610	72.233	34.925	25.4
b	HM 89449/410	76.2	36.512	29.37
c	HM 801346/310	82.55	38.1	29.37
d	HM 803146/110	88.9	41.275	30.162
e	HM 807040/010	104.775	44.45	36.512

Table 6.1: Analysed rolling bearings.

This results permitted to conclude, that the model presents a reasonable influence of the different variables, in terms of tendency and values. It should be noticed that one of the presented rolling bearings (b) does not present the correct tendency, as it decreases the power loss, although the associated error appears to be low.

6.2.2 Crown Wheel

For the crown wheel, it was also not possible to separate the churning losses from the rolling bearings. The results presented in Figure 6.11 were obtained from the test with crown wheel mounted, and then it was subtracted the pinion and rolling bearings test. So the experimental results presented in Figure 6.11, represents the crown wheel churning, the gears squeezing and the crown wheel rolling bearings.

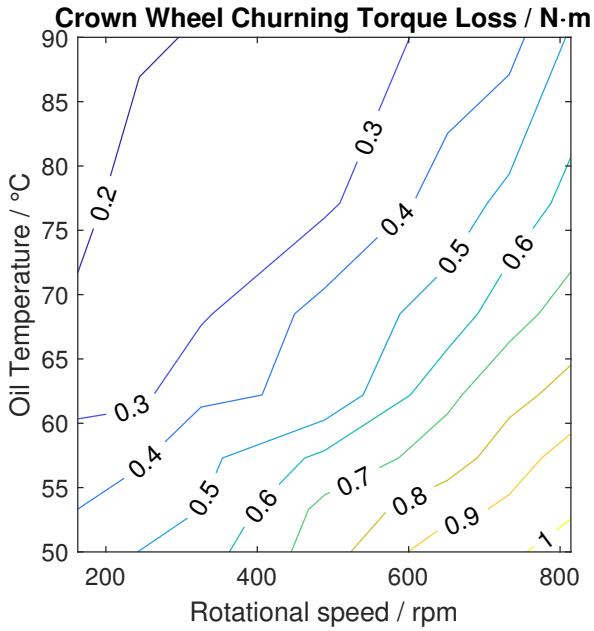
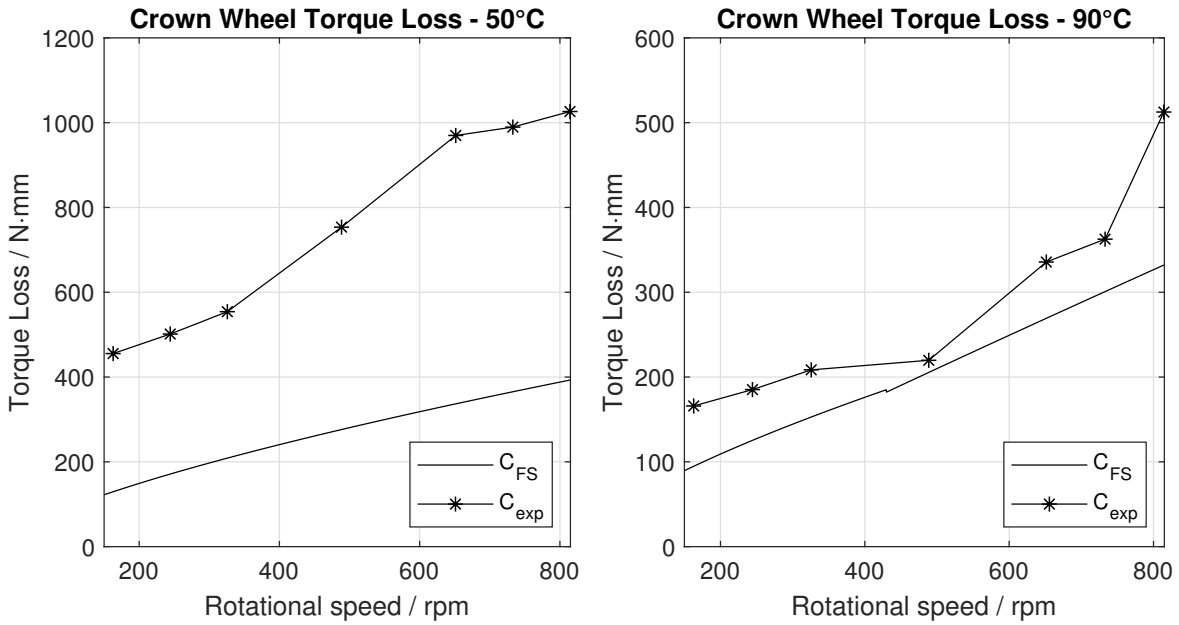


Figure 6.11: Crown wheel torque loss variation with speed and temperature.

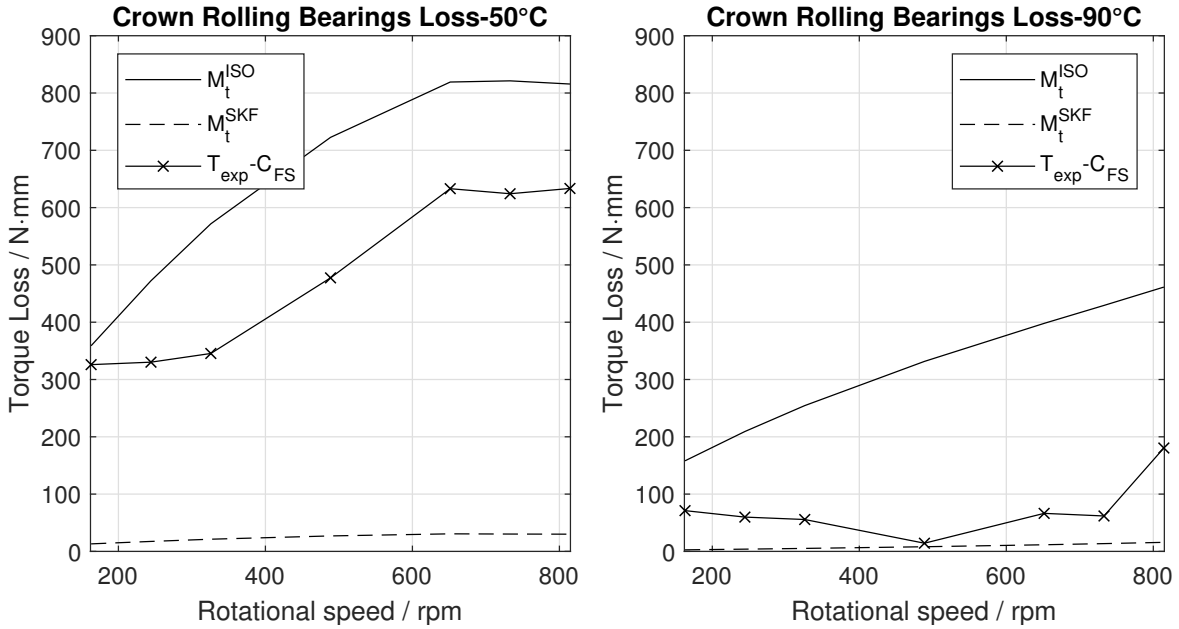
In Figure 6.12, it is possible to compare the crown wheel experimental results with the Fossier [1] model.



(a) Crown torque loss at 50 °C. **(b)** Crown torque loss at 90 °C.

Figure 6.12: Churning torque loss models comparison with the experimental results.

It is possible to conclude that the Fossier [1] model present a tendency that is in aggreement with the experimental results, that includes both the crown wheel churning, rolling bearings and gears squeezing losses.



(a) Crown torque loss at 50 °C. **(b)** Crown torque loss at 90 °C.

Figure 6.13: Rolling bearing torque loss models comparison with the experimental results.

In order to obtain the crown wheel rolling bearings losses, the Fossier [1] model was subtracted to the experimental results. In this case, it is possible to verify that maybe ISO [29] presents the most realistic model, although these results are not very trustworthy. Especially in Figure 6.13a, it is possible to verify the influence of the lubrication methods, explained in chapter 5.3.1, where at 1000 rpm it is possible to verify the change of lubrication method. It can be visualised a torque drop with the increase of speed, as oil flow decrease of oil flow rate through the shaft hole up to 1000 rpm, where stops the oil coming through the shaft and begins the lubrication through the channel, that increases the flow rate with the increase of speed.

7 Conclusions and Future Works

7.1 Conclusions

This study aimed to understand and model the power loss of a rear axle, specifically the no-load losses. Based in experimental tests, this study lead to some conclusions, although a few problems were found during this tests, due to the difficulty of separating the different power loss contributors, as the churning from the rolling bearings losses.

During the experimental tests, it was possible to verify the difficulty of simulate the oil bath lubrication conditions, using oil circulation system. At the end of the tests, it was also possible to check that pinion churning losses represents a small fraction, when compared to the pinion rolling bearings, approximately 2.7 %, explaining the difficulty of this results experimentally, as the test rig does not have enough sensibility. This is explained by the pinion rolling bearings high contribution, due to high preload that they are subjected to.

By analysing all the obtained results, it was possible to verify the many models that already exist in the literature regarding this topics, as well analyse the many influences that can be felt in the power loss of a rear axle.

Regarding the tests that were performed to the lubricant, it was possible to conclude that the presented models can represent the oil characteristics, viscosity and density, with the temperature variations. This allows to have more trust in this models, when the experimental data can not be obtained.

During the experimental tests, it was not possible to separate the churning from the rolling bearings losses. Anyway the Fossier [1] model was compared to the experimental results, presenting a tendency that is in agreement with the experimental results, especially in the crown wheel results, where the rolling bearings have a lower contribution, narrowing the acceptable values for the churning losses.

In relation to rolling bearings, the Fossier [1] and Simrit [32] models were subtracted to the pinion shaft losses, in order to obtain just the rolling bearings power loss. As the churning only represents small fraction of the pinion losses, it was assumed that the associated error will be low and the rolling bearings preload is unknown, so only the trend of the results can be verified. This allowed to develop a model capable of predict the power loss. The same can not be verified for the crown wheel, where the higher contribution is from the churning losses, due to the rolling bearings low preload. As the Fossier [1] model overestimates, in this case were obtained results that make no sense, although it was possible to verify the lubrication method change in the results. For the pinion, it was possible to analyse the tendency of the experimental results, that can not be confirmed by the models. The experimental results tends to a constant value of torque loss with the increase

of the rotational speed.

From all the different losses contributors, it is possible to aim that their losses increase with the increase of speed and decrease of temperature.

Finally, a global analyses allowed to conclude that crown wheel loss represents only 31 % of the total power losses. This can be explained by the high preload that the pinion rolling bearings are subjected to, meanwhile the crown wheel rolling bearings are only subjected to a preload that assures that there is no play in the assembly. So main contributor for the differential losses are the pinion rolling bearings.

7.2 Future Work

As explained before, not all the objectives could be fulfill, due to difficulties that were found during the experimental test. Therefore some notes are left with some ideas/improvements for future works:

- Separate the hypoid gear from the shaft, making some changes to make possible to assemble/disassembled the gear when is need and assuring a correct positioning. This would allow to study the pinion churning and rolling bearings losses, but also any gear that could be assembled, in an optimised churning ambient that is created by the differential oil deflectors.
- Adapt a load washer transducer to the pinion rolling bearing shaft, were it would be possible to do a complete analyses to the tapered rolling bearing, taking into account the preload, oil temperature, rotational speed and lubrication method. This would also allow to create a more realistic power loss model.
- Perform experimental test with only the crown wheel mounted in the differential. So the planet and sun gears should be blocked, removing the differential function and simulating a straight line driving. Design a shaft that could transmit the power from the test rig to the differential output shaft and adapt an oil circulation system to the rolling bearings. The idea is to simulate the same lubrication method to the rolling bearings, meanwhile the differential is bath lubricated or not. With this tests, it would be possible to obtain the crown wheel churning and rolling bearings separated, including the squeezing losses if the pinion gear has removed.

If any problems were found during the experimental tests, it would be possible to separate all the different losses contributors, except separate both pinion rolling bearings losses, allowing to present a complete power loss model.

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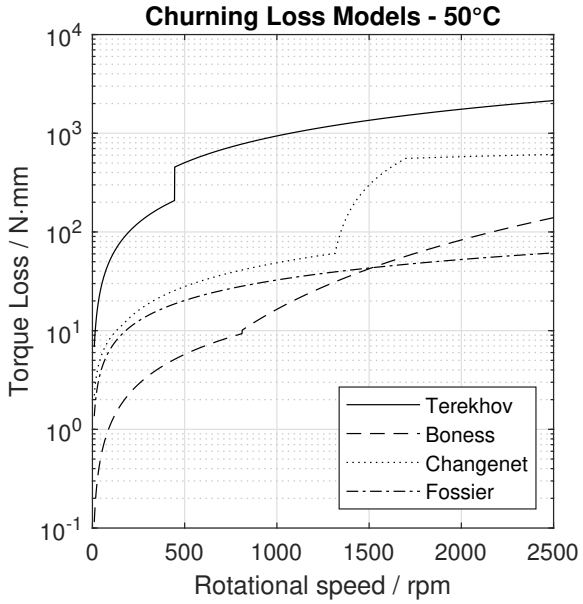
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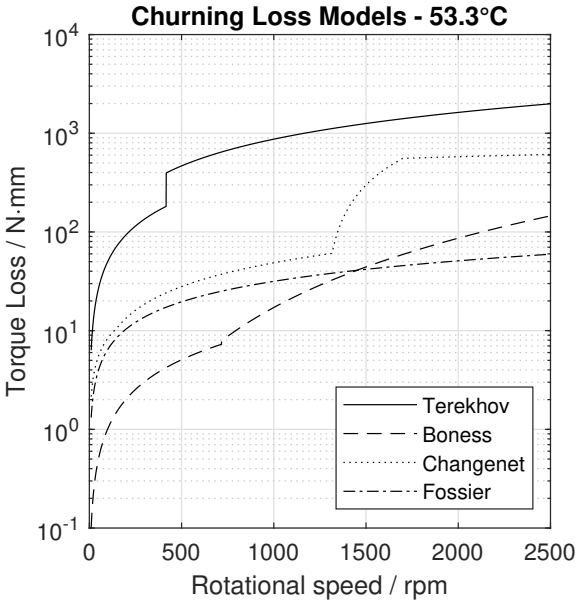
A Charts

A.1 Churning Torque Loss Models comparison

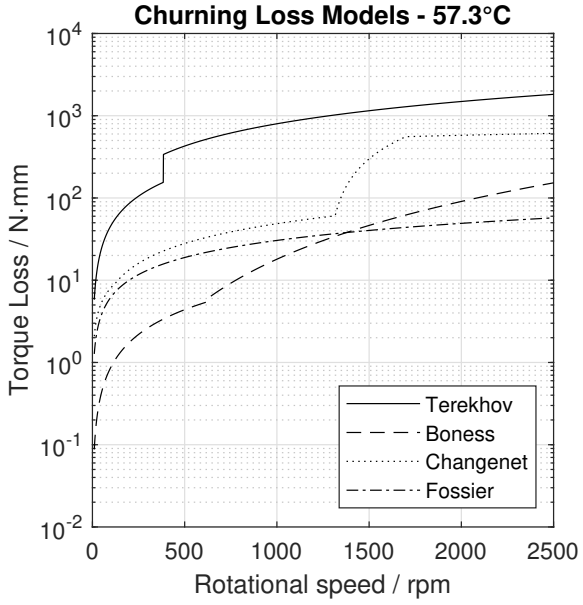
A.1.1 Pinion Torque Loss



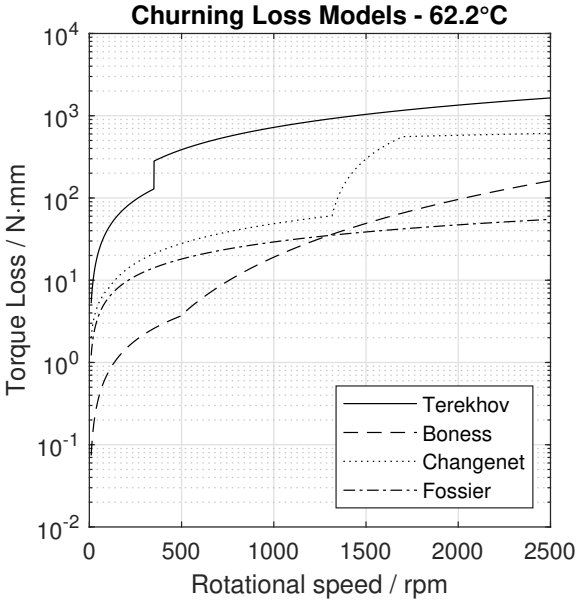
(a) 50°C.



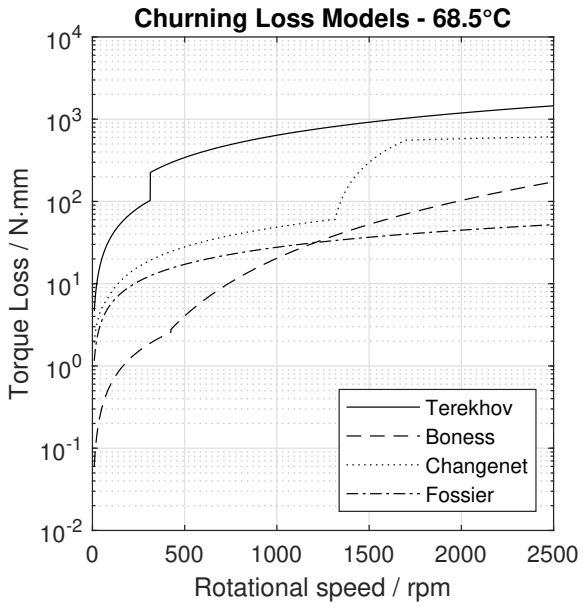
(b) 53.3°C.



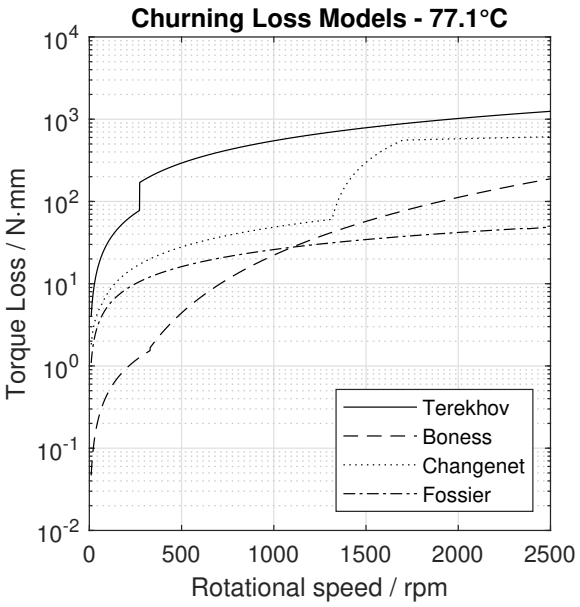
(c) 57.3°C.



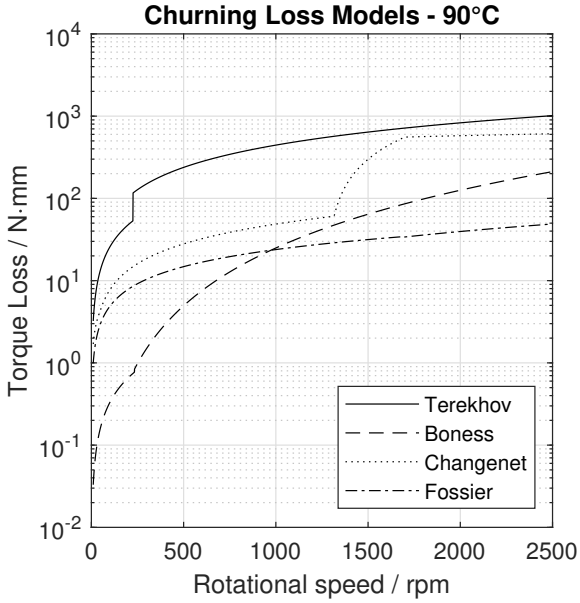
(d) 62.2°C.



(e) 68.5°*C*.



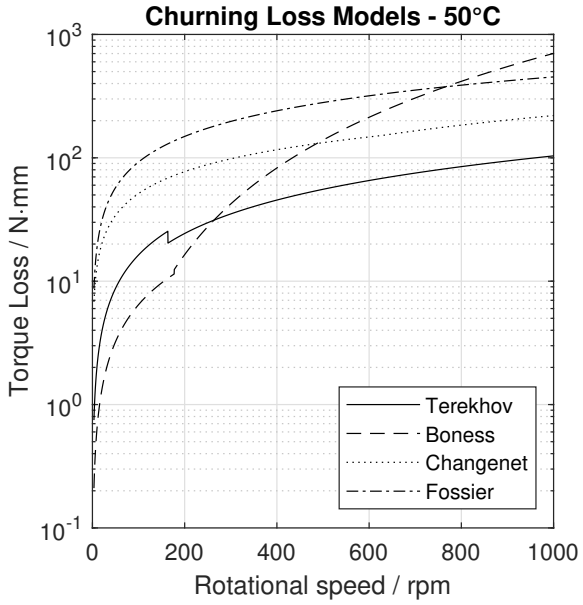
(f) 77.1°*C*.



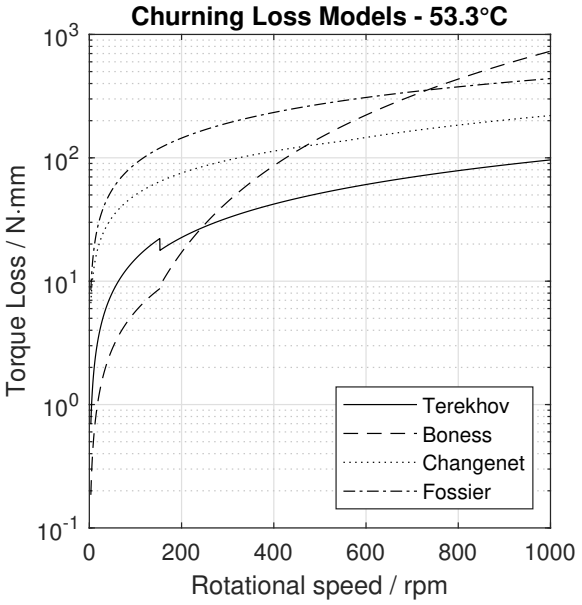
(g) 90°*C*.

Figure A.1: Pinion churning torque loss models comparison with the experimental results.

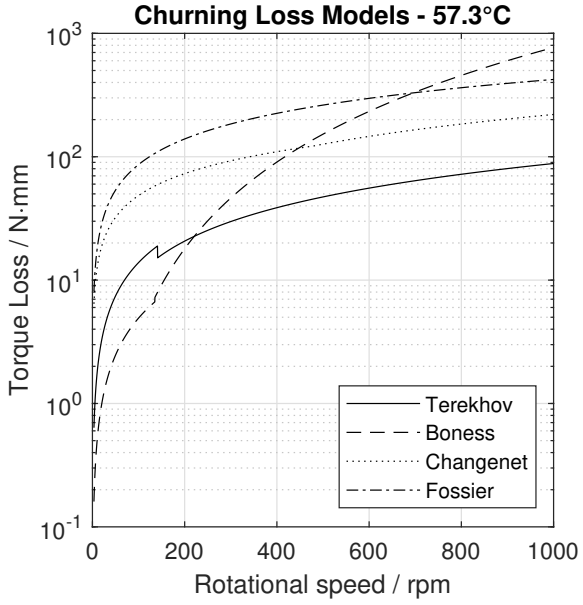
A.1.2 Crown Torque Loss



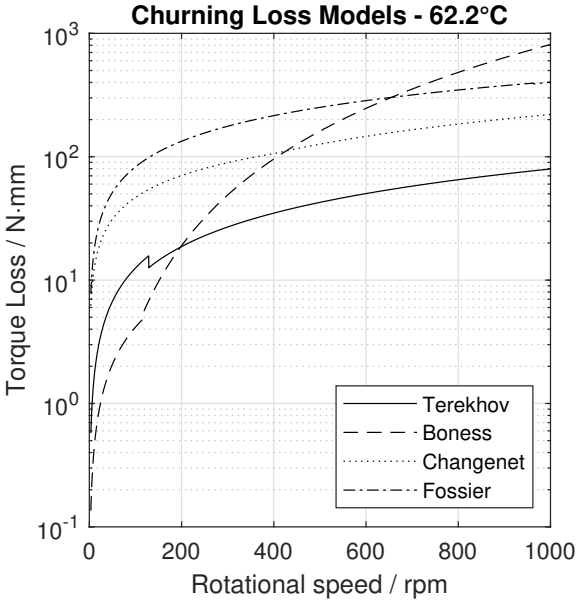
(a) 50°C.



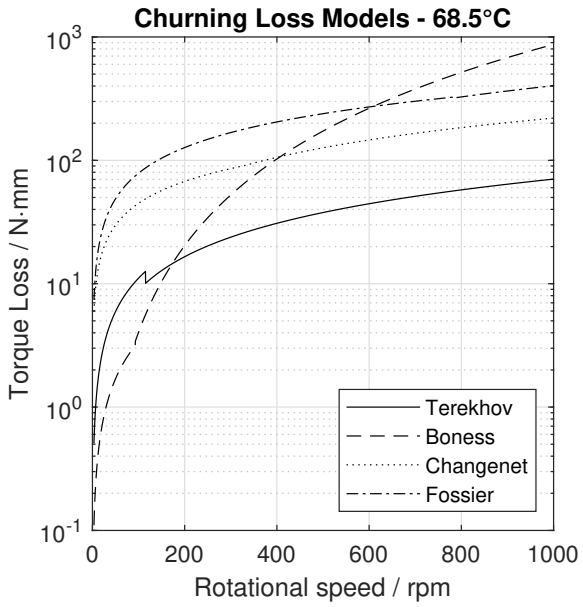
(b) 53.3°C.



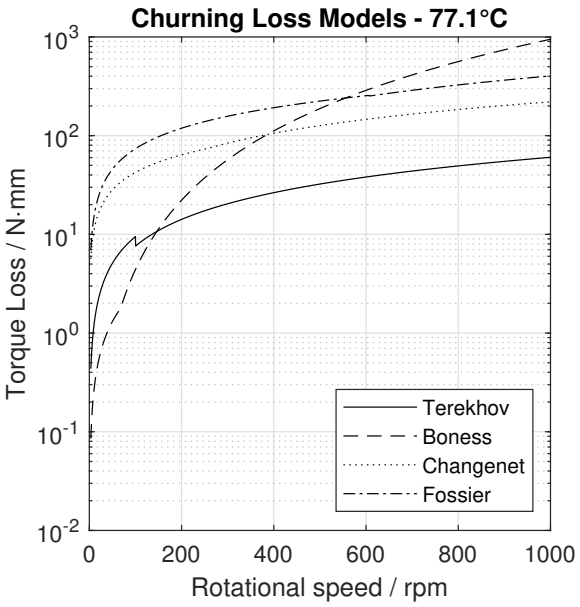
(c) 57.3°C.



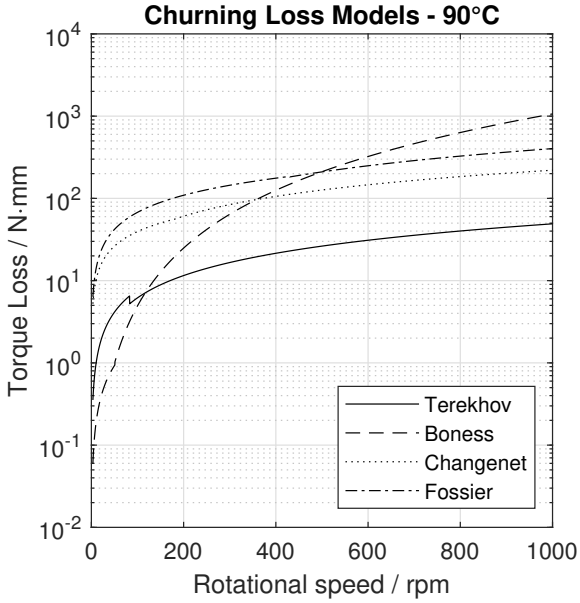
(d) 62.2°C.



(e) 68.5°*C*.



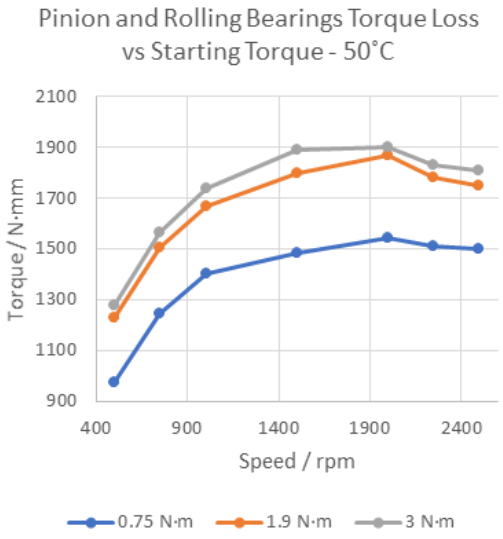
(f) 77.1°*C*.



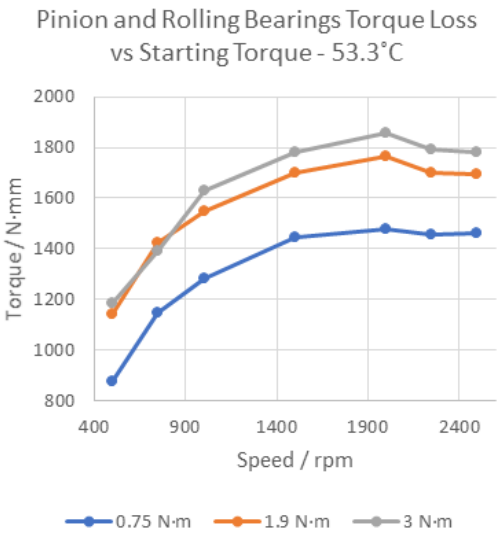
(g) 90°*C*.

Figure A.2: Crown wheel churning torque loss models comparison with the experimental results.

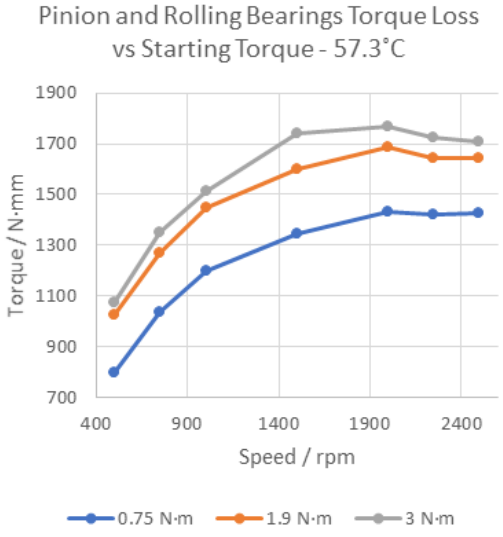
A.2 Starting Torque influence on the Pinion and Rolling Bearings torque loss



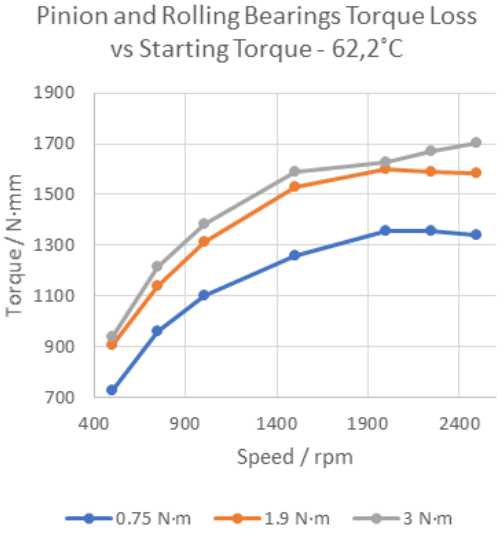
(a) 50°C.



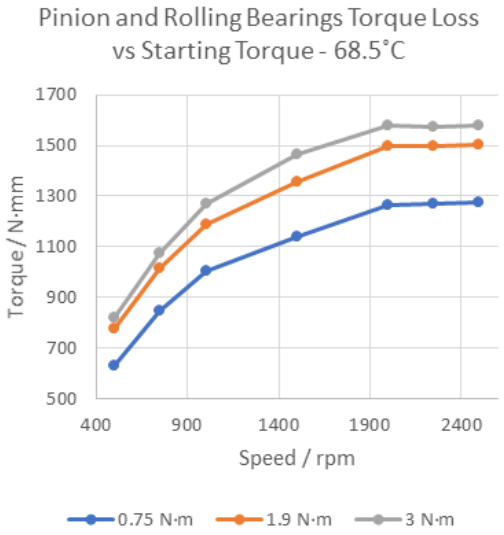
(b) 53.3°C.



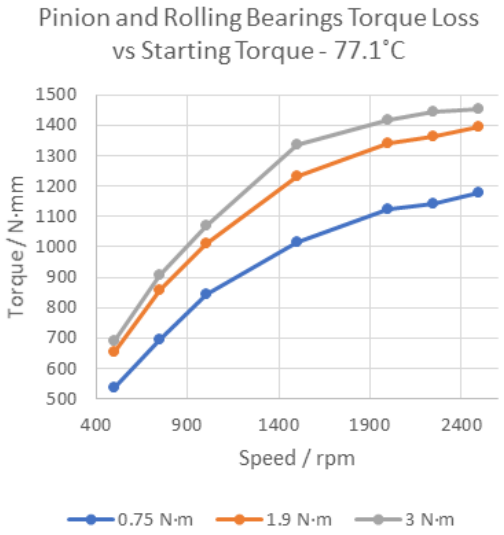
(c) 57.3°C.



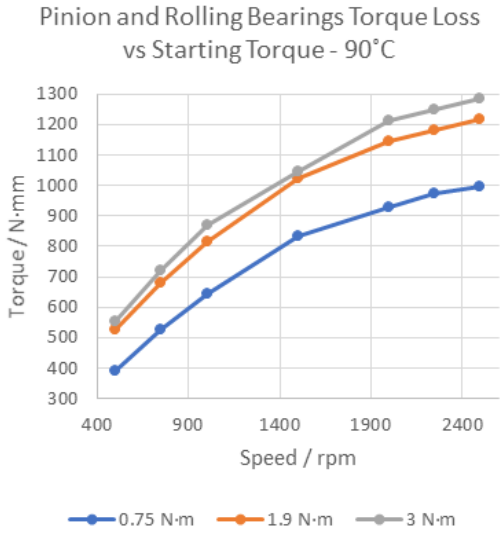
(d) 62.2°C.



(e) 68.5°C.



(f) 77.1°C.



(g) 90°C.

Figure A.3: Pinion and crown wheel torque loss comparison between different starting torque.

A.3 Rolling Bearings Torque Loss comparison between different Oil Flow Rates

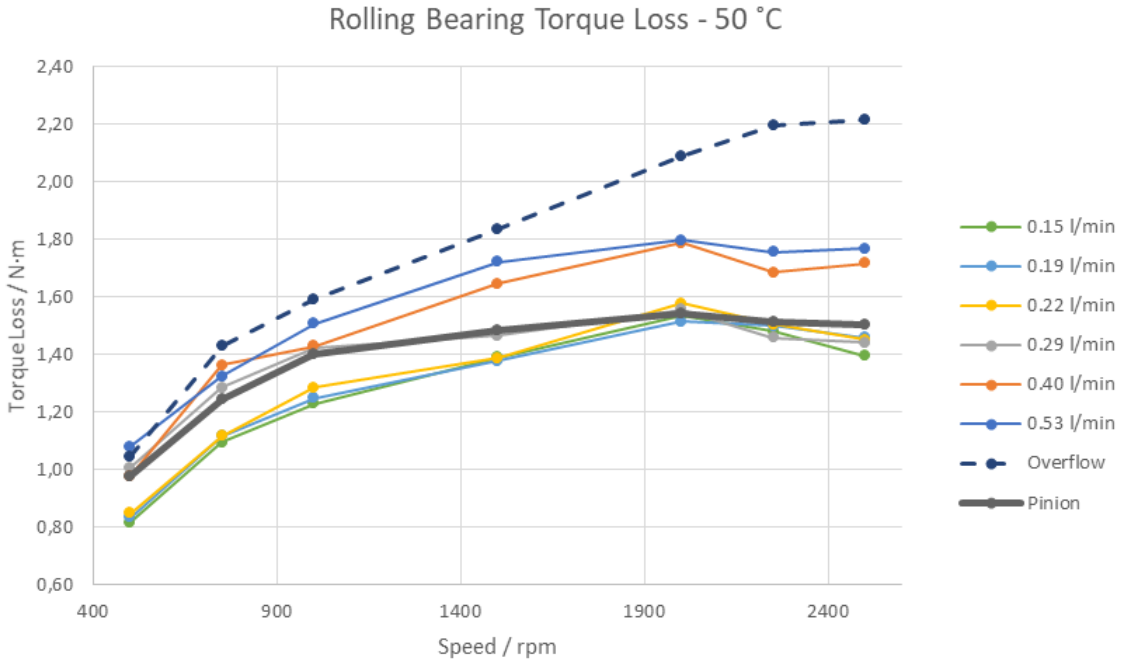


Figure A.4: Rolling bearings torque loss comparison at 50 °C.

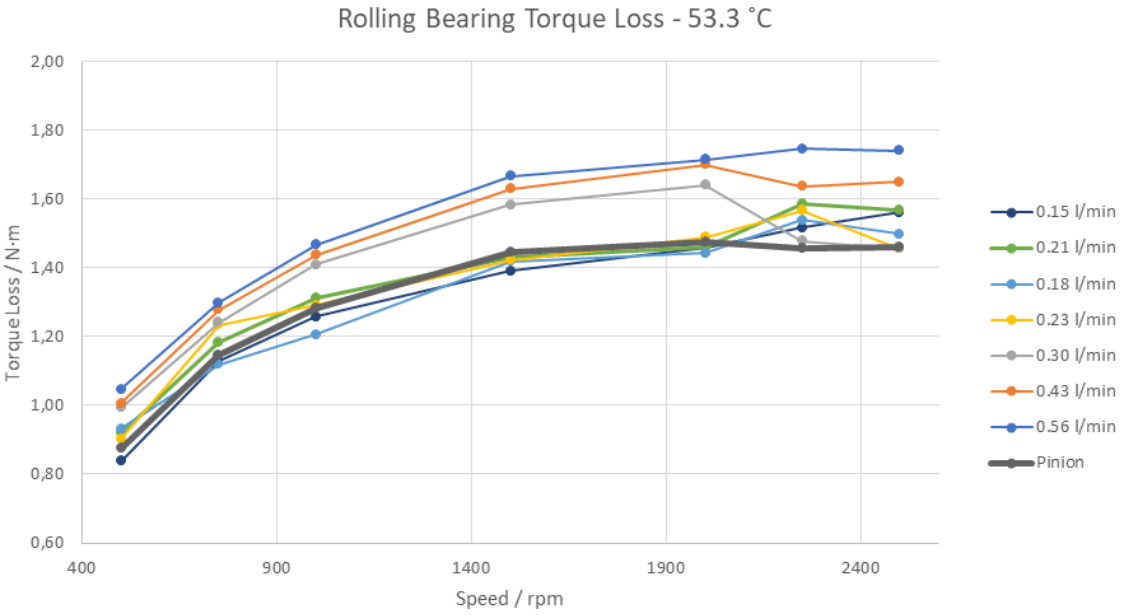


Figure A.5: Rolling bearings torque loss comparison at 53.3 °C.

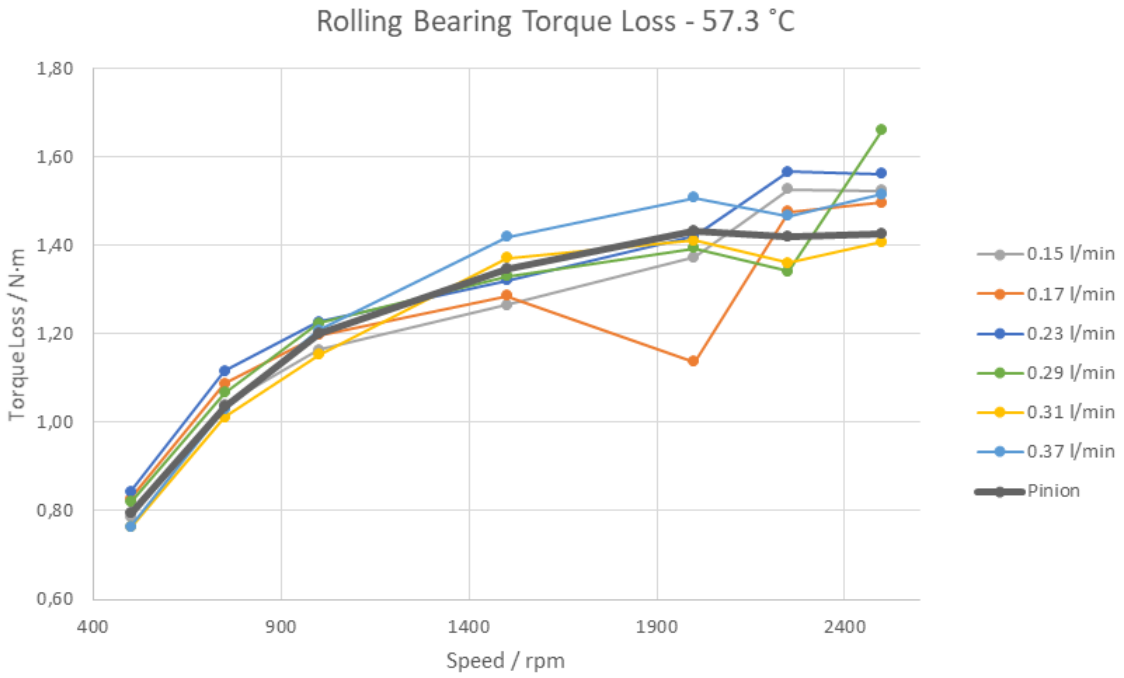


Figure A.6: Rolling bearings torque loss comparison at 57.3 °C.

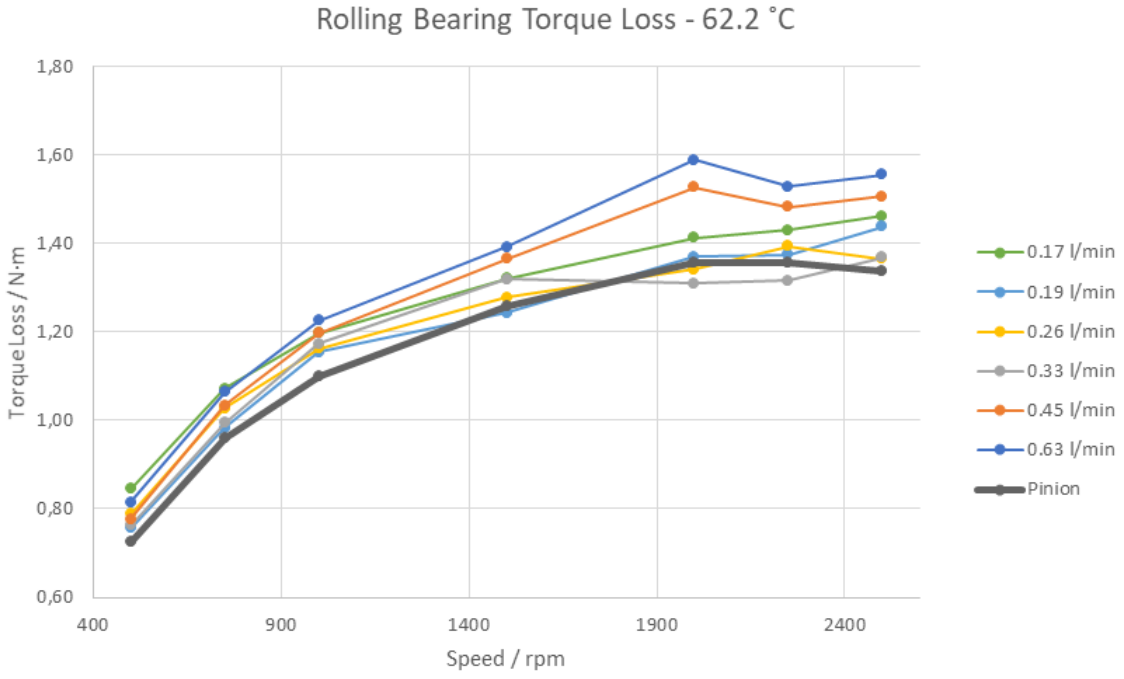


Figure A.7: Rolling bearings torque loss comparison at 62.2 °C.

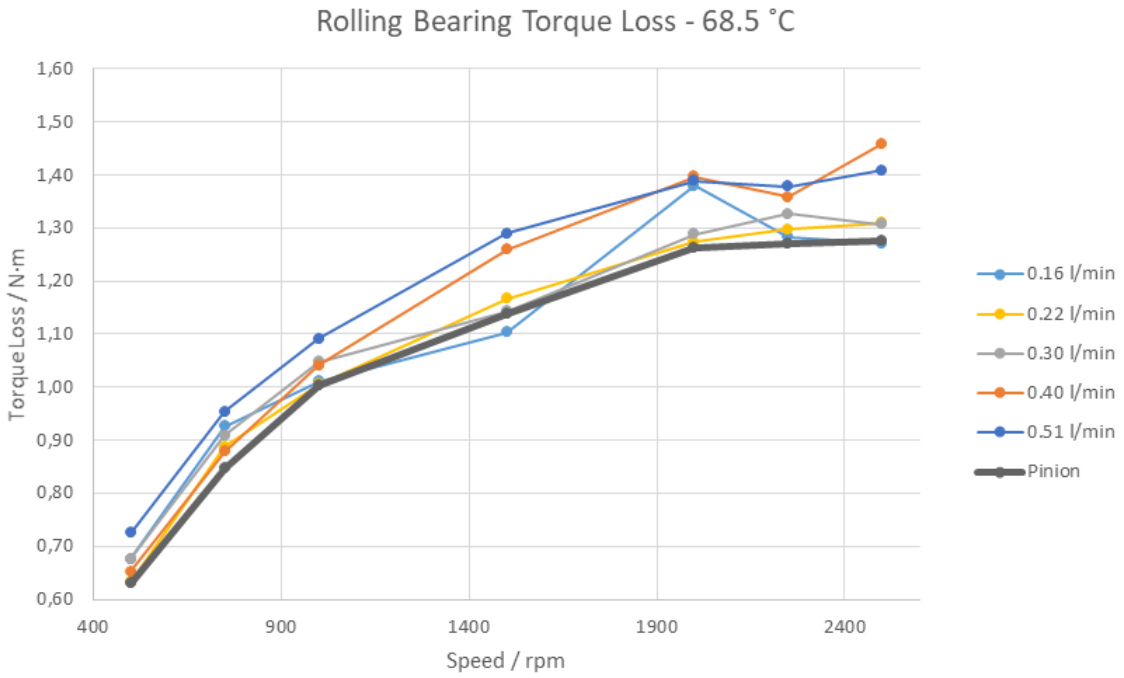


Figure A.8: Rolling bearings torque loss comparison at 68.5 °C.

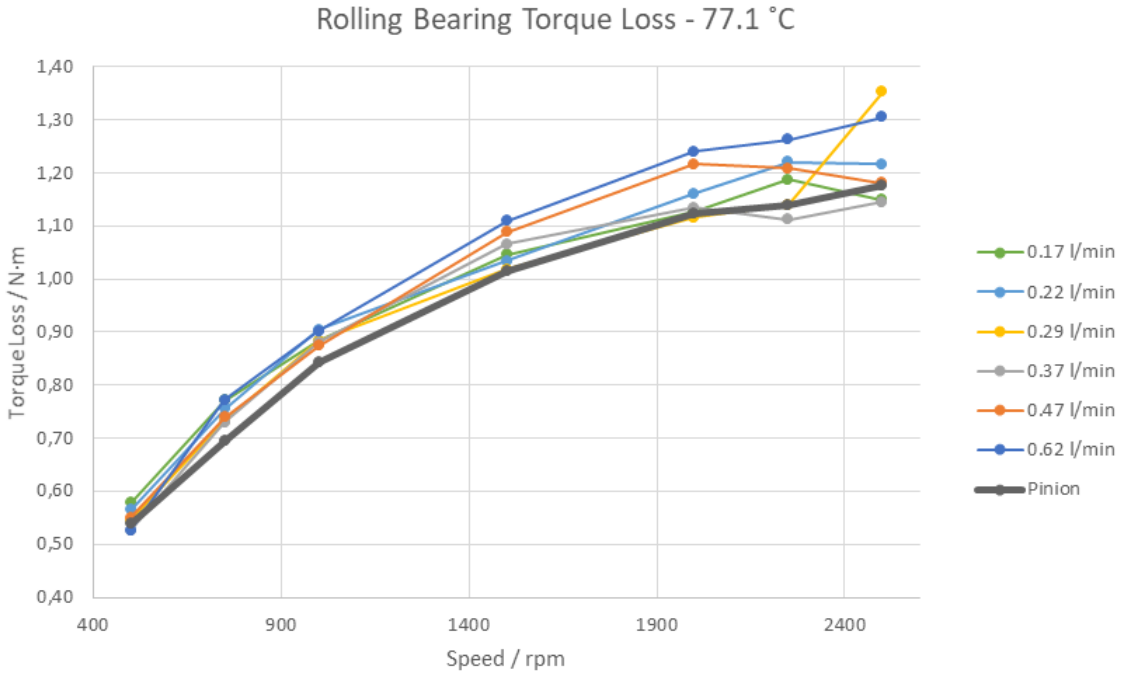


Figure A.9: Rolling bearings torque loss comparison at 77.1 °C.

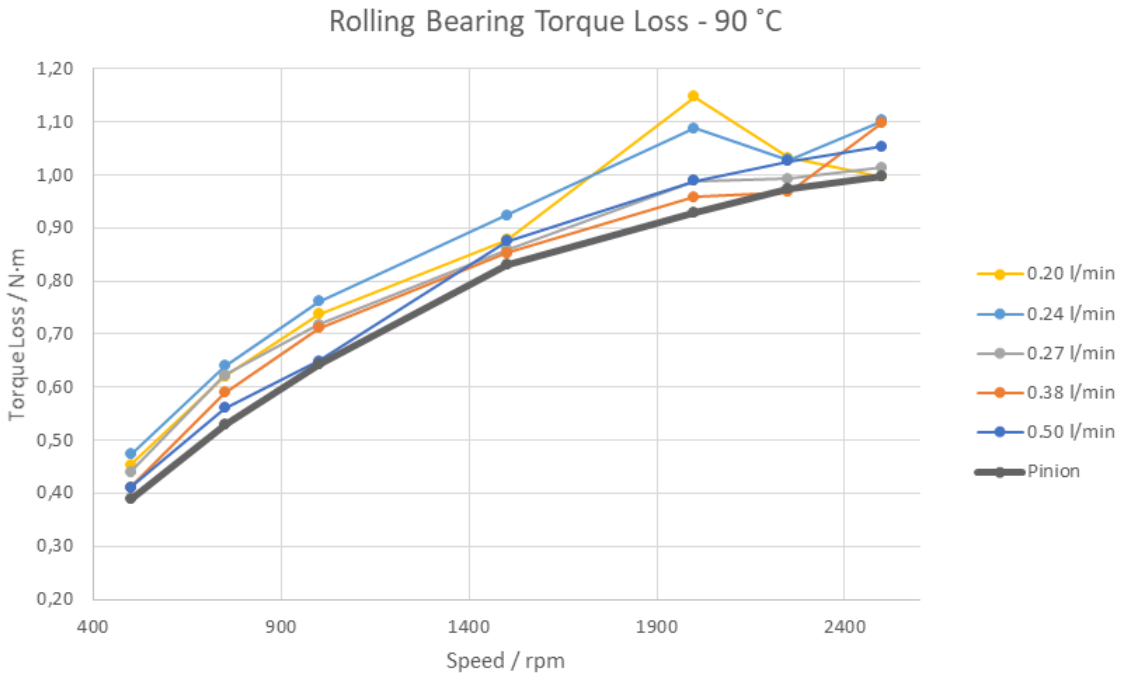
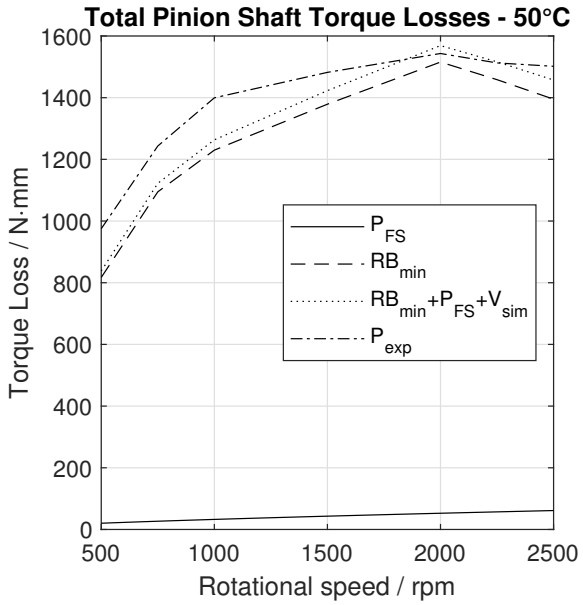


Figure A.10: Rolling bearings torque loss comparison at 90 °C.

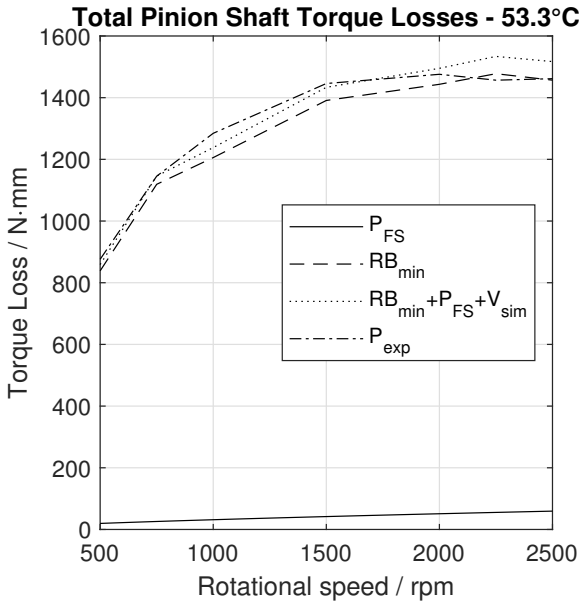
A.4 Results analyses

A.4.1 Pinion results

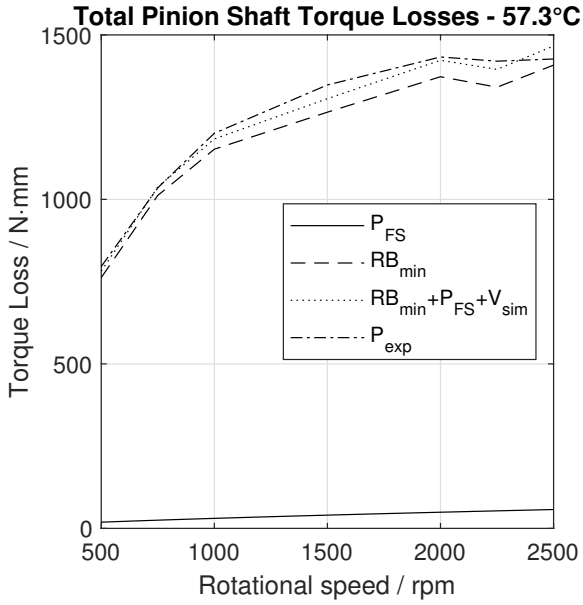
Churning comparison



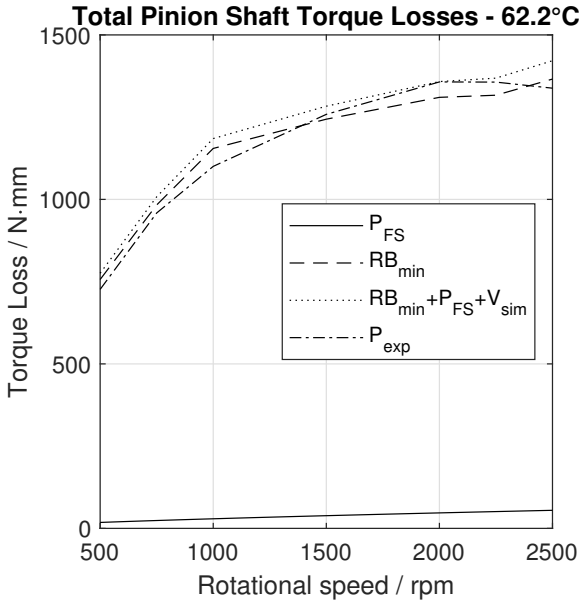
(a) $50°C$.



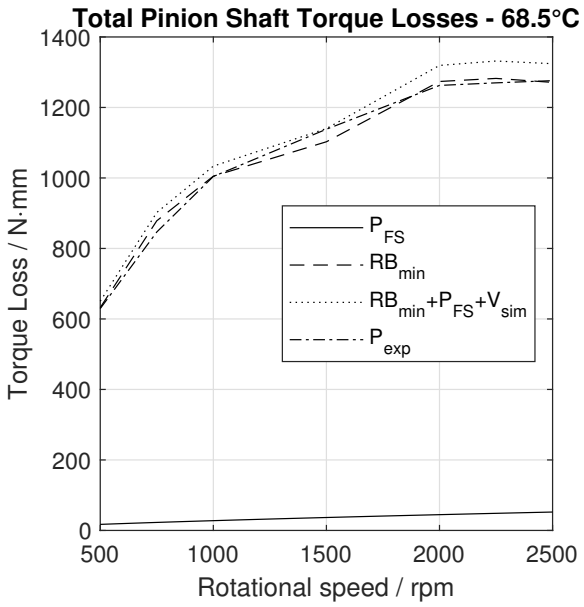
(b) $53.3°C$.



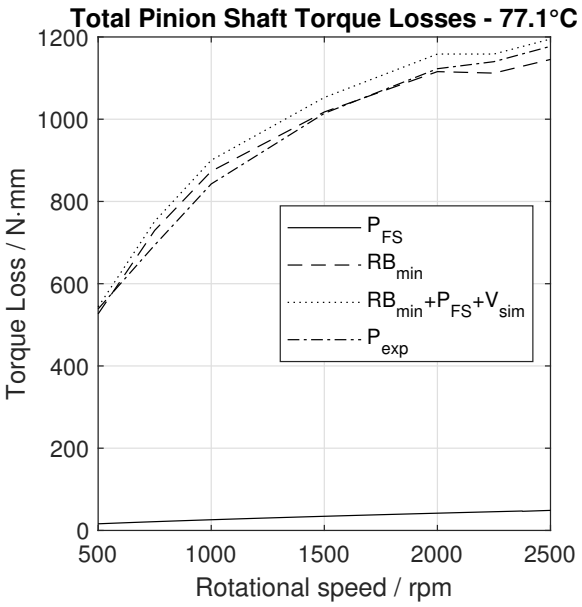
(c) $57.3°C$.



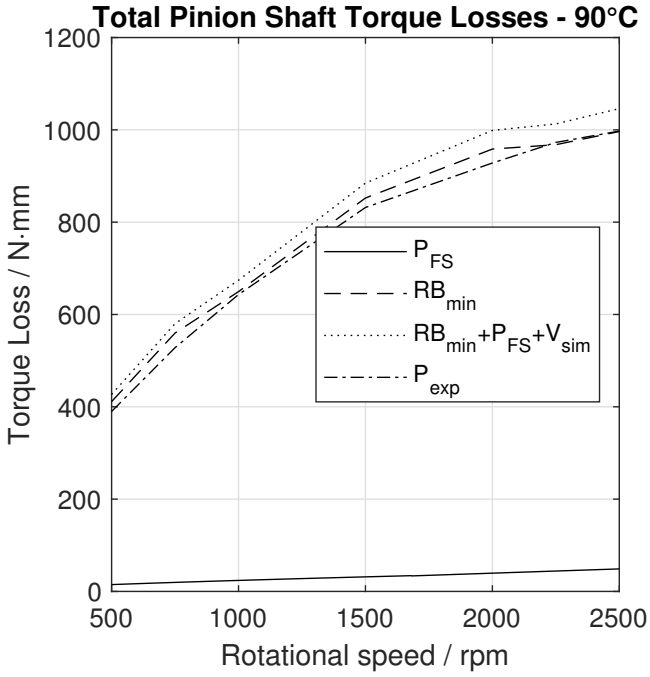
(d) $62.2°C$.



(e) 68.5°*C*.



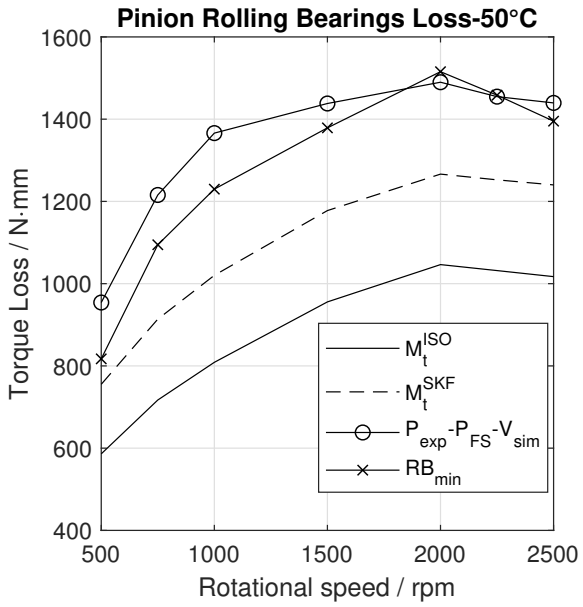
(f) 77.1°*C*.



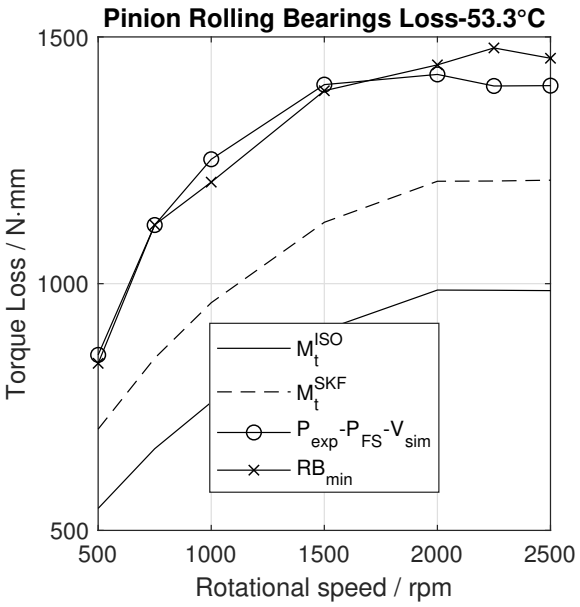
(g) 90°*C*.

Figure A.11: Pinion rolling bearings torque loss models comparison with the experimental results.

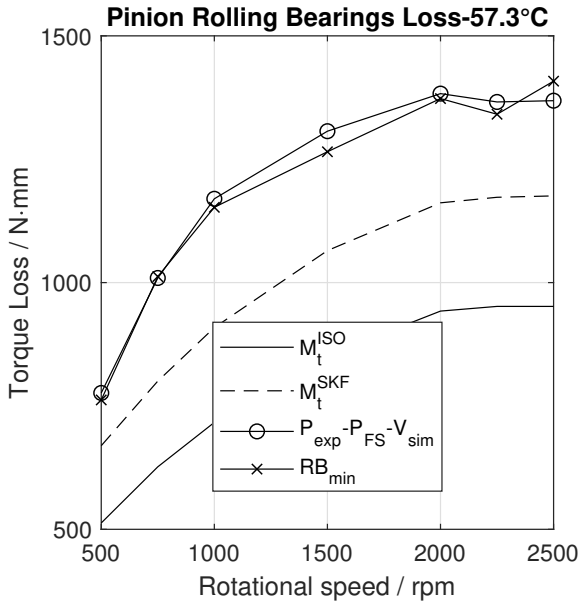
Rolling bearings comparison



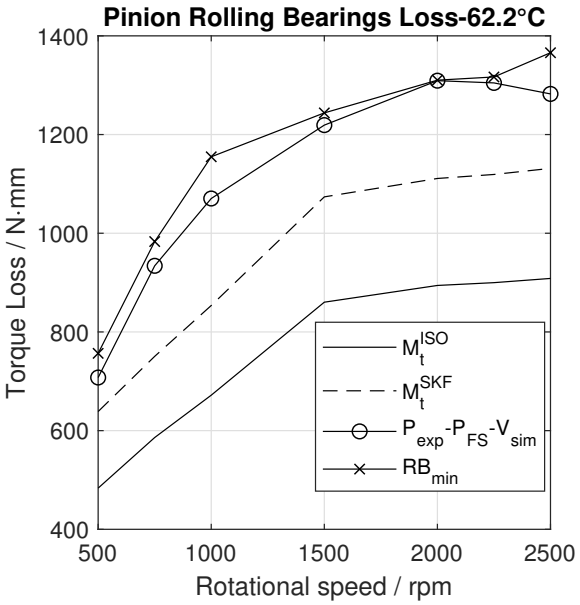
(a) 50°C.



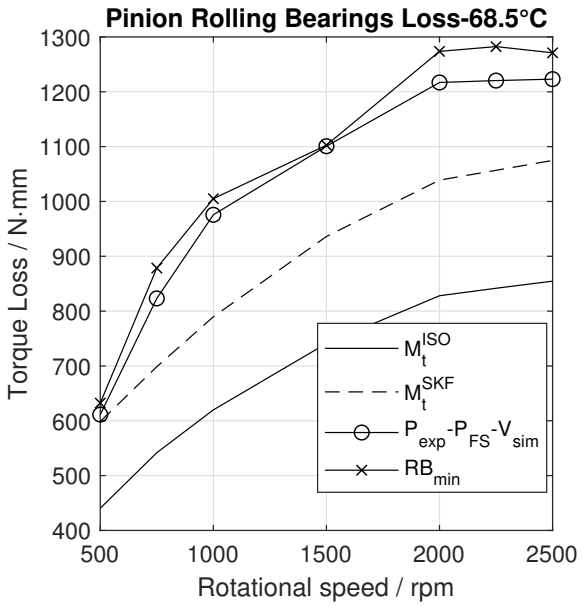
(b) 53.3°C.



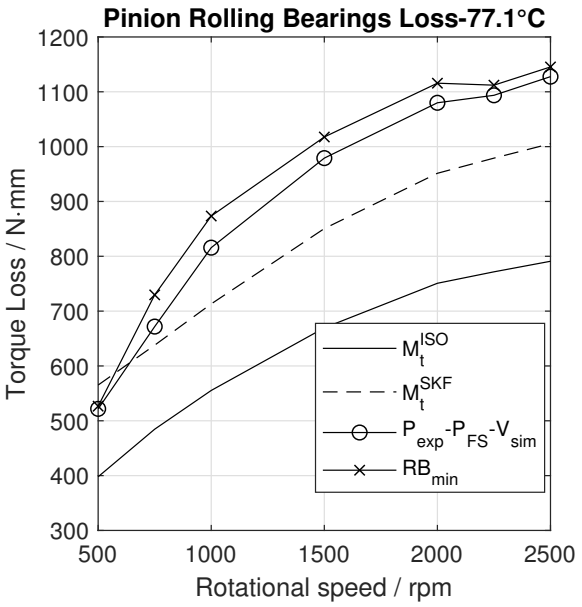
(c) 57.3°C.



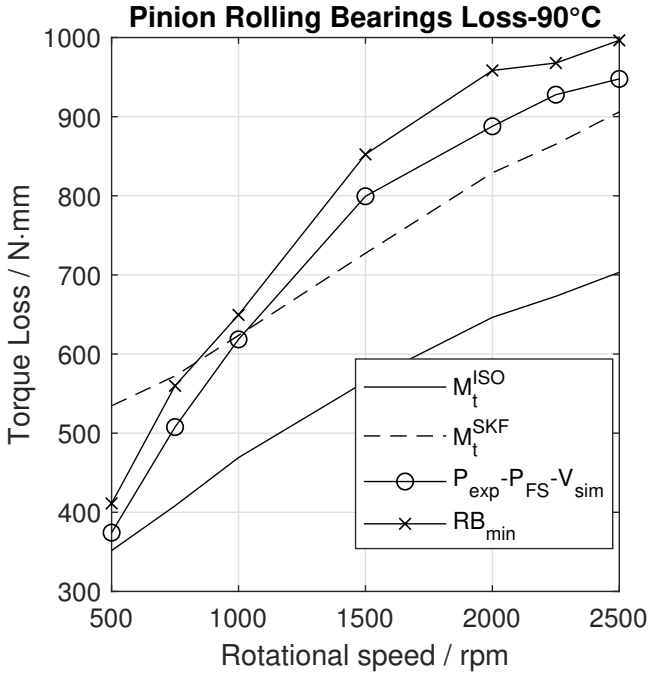
(d) 62.2°C.



(e) 68.5°*C*.

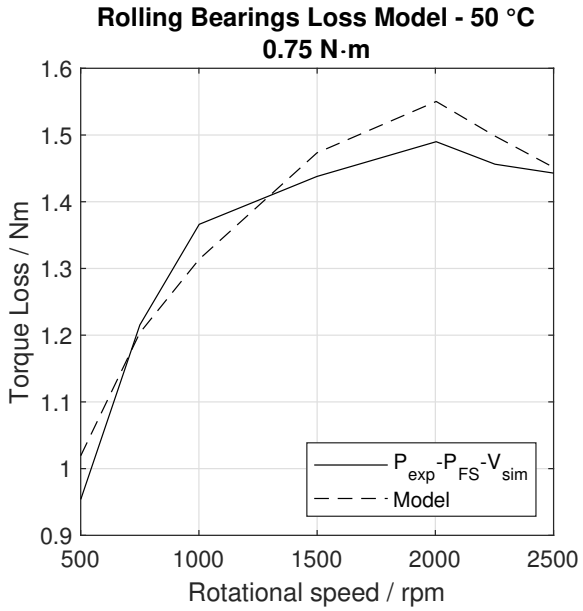


(f) 77.1°*C*.

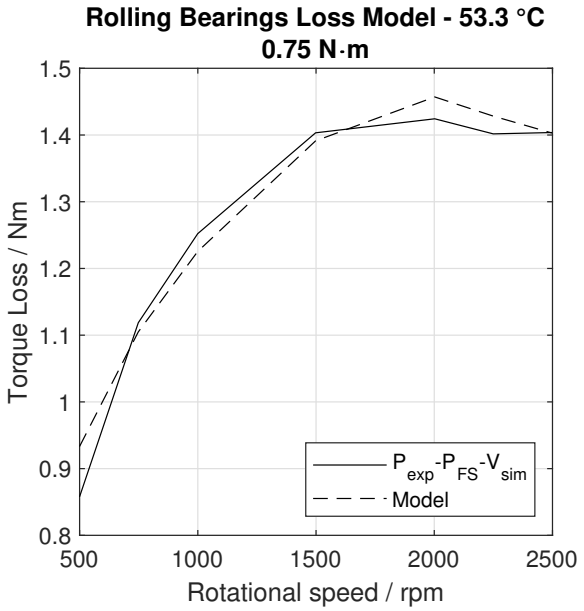


(g) 90°*C*.

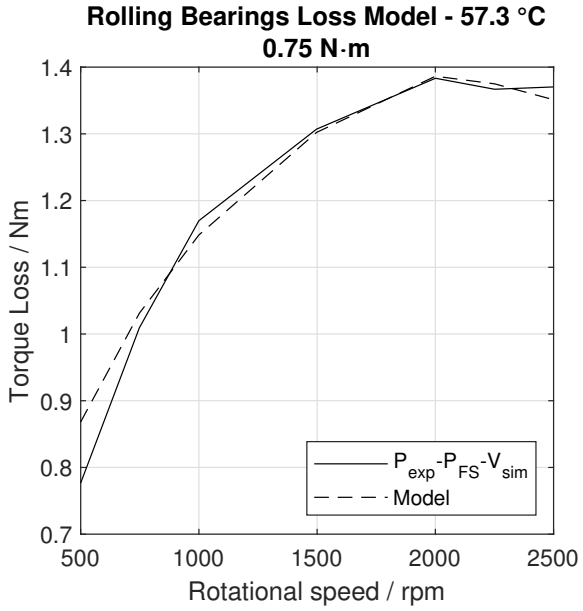
Figure A.12: Pinion rolling bearings torque loss models comparison with the experimental results with a starting torque of 0.75 N·m.



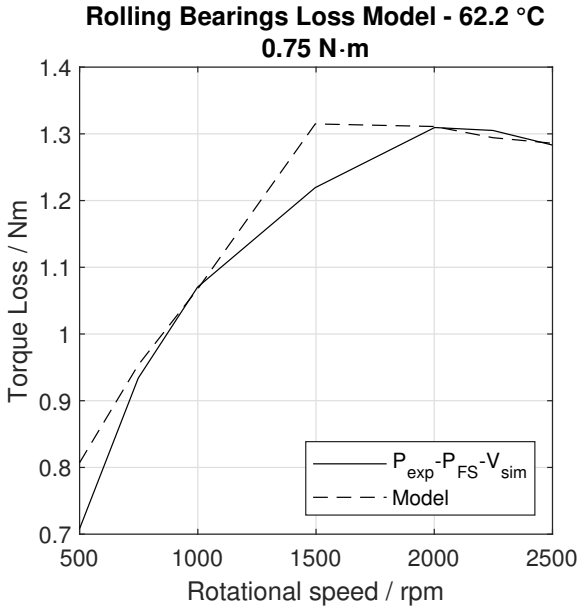
(a) 50°C.



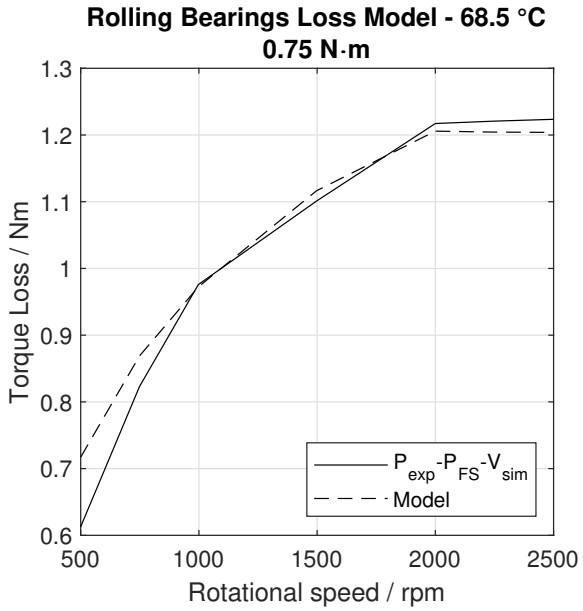
(b) 53.3°C.



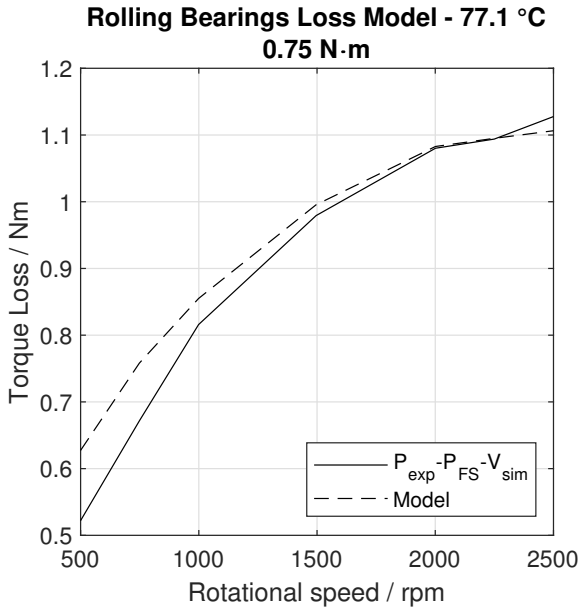
(c) 57.3°C.



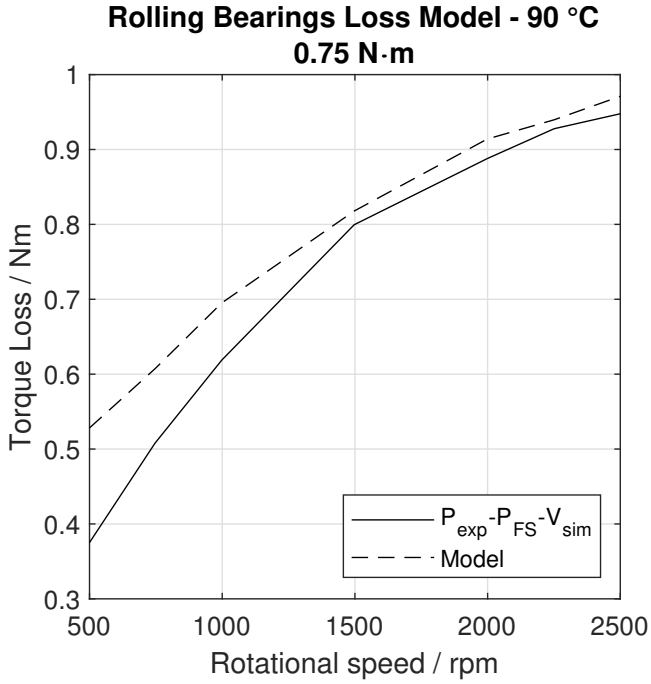
(d) 62.2°C.



(e) 68.5°C.

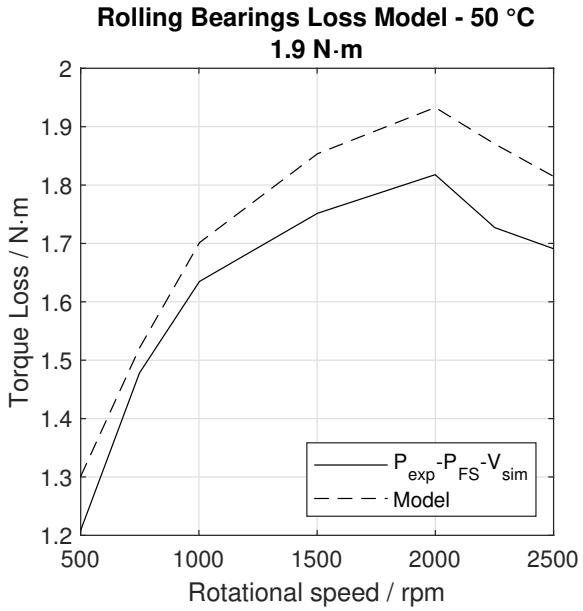


(f) 77.1°C.

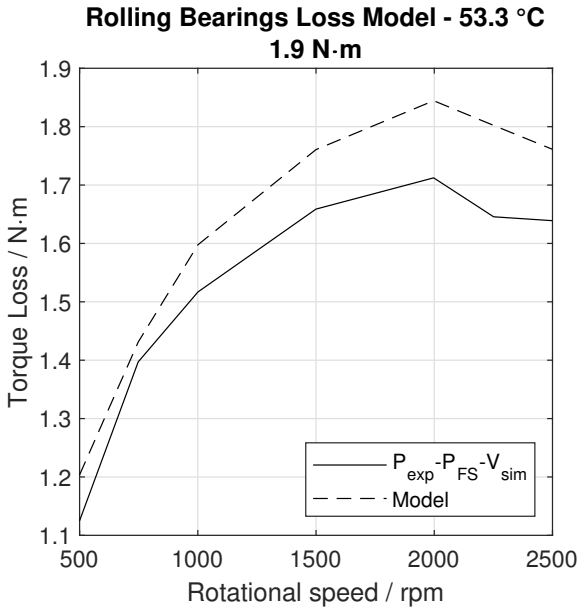


(g) 90°C.

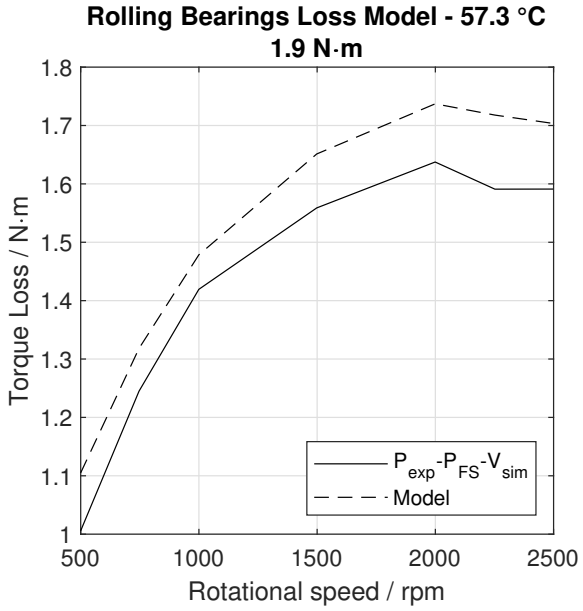
Figure A.13: Pinion rolling bearings torque loss model comparison with the experimental results with a starting torque of 0.75 N·m.



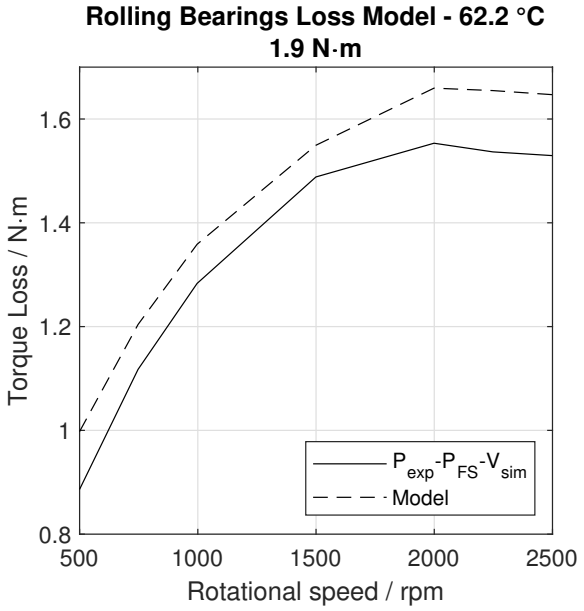
(a) $50°C$.



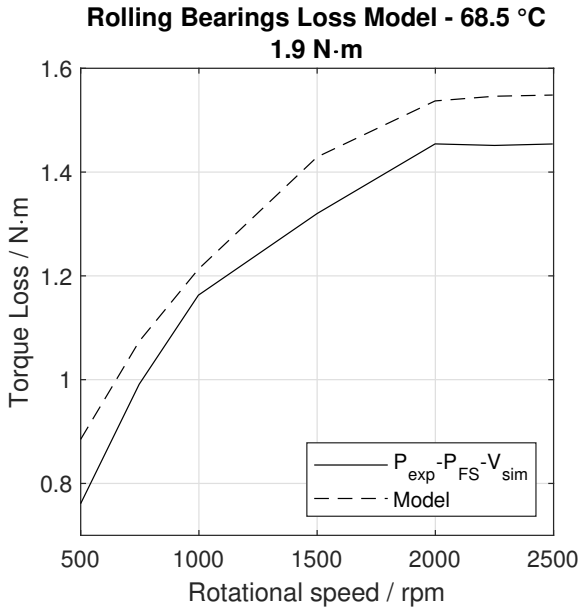
(b) $53.3°C$.



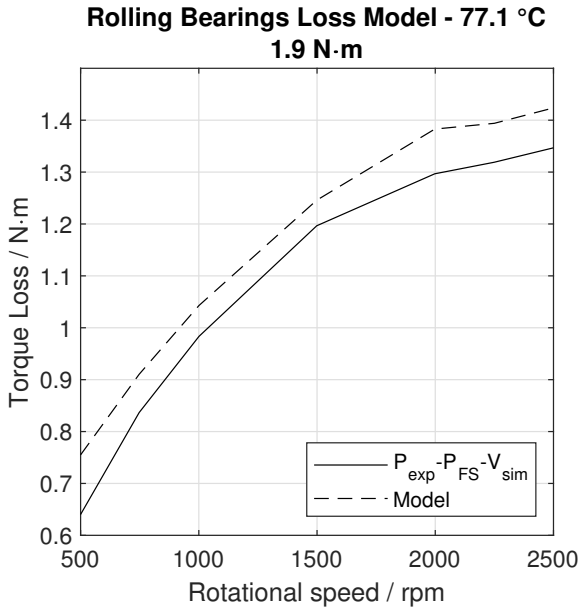
(c) $57.3°C$.



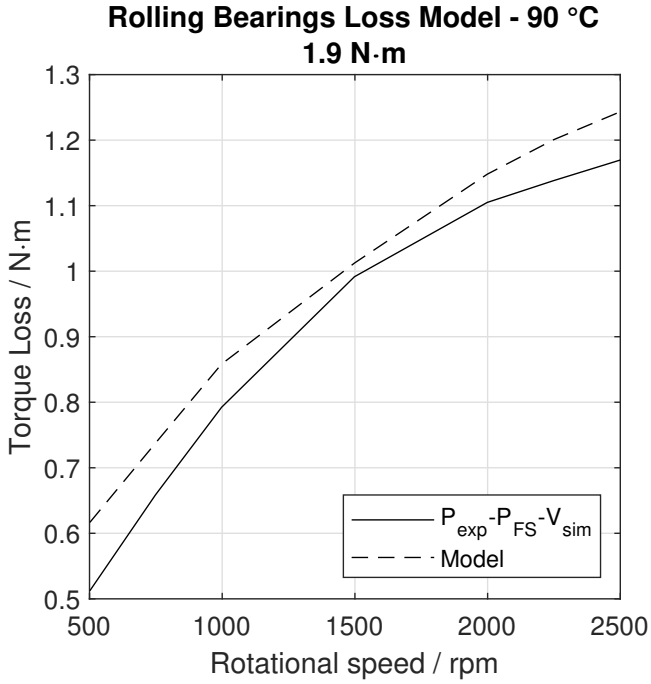
(d) $62.2°C$.



(e) 68.5°*C*.

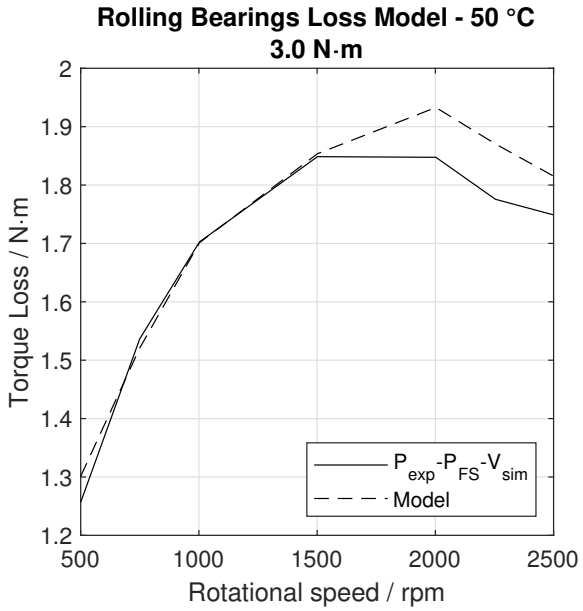


(f) 77.1°*C*.

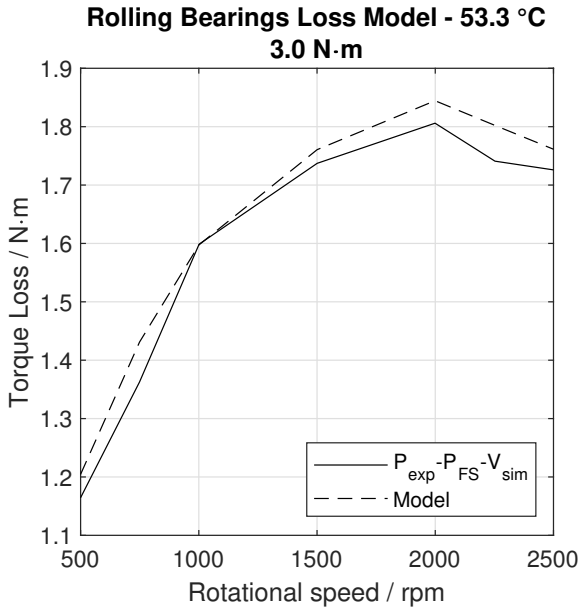


(g) 90°*C*.

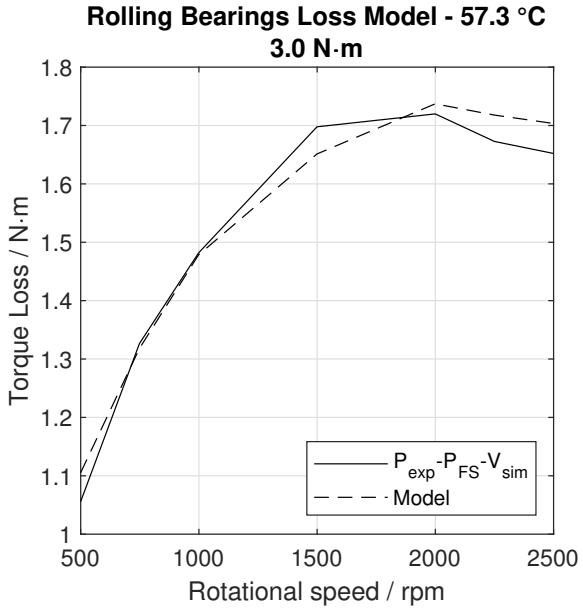
Figure A.14: Pinion rolling bearings torque loss model comparison with the experimental results with a starting torque of 1.9 N·m.



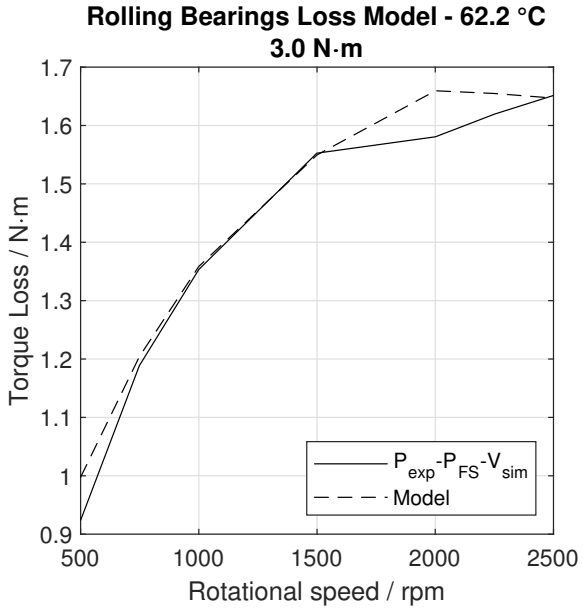
(a) $50°C$.



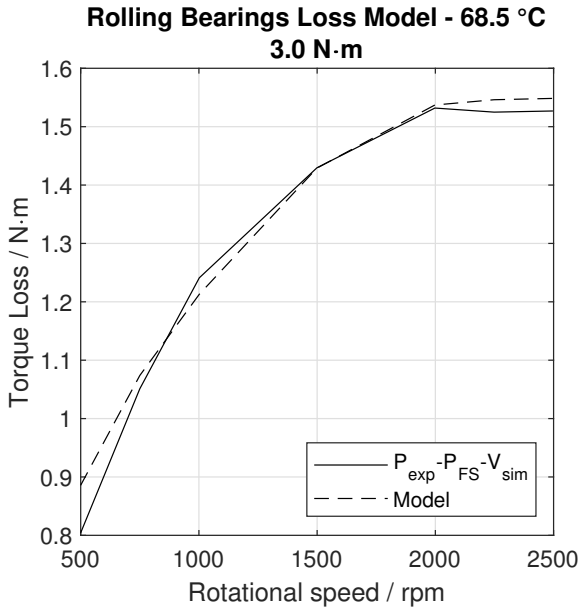
(b) $53.3°C$.



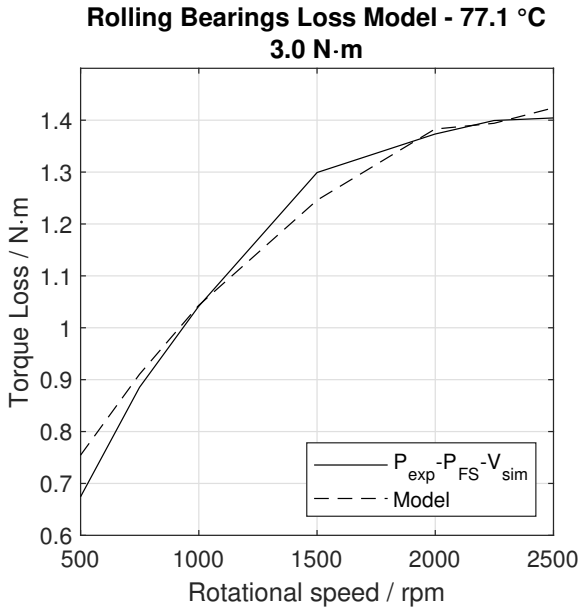
(c) $57.3°C$.



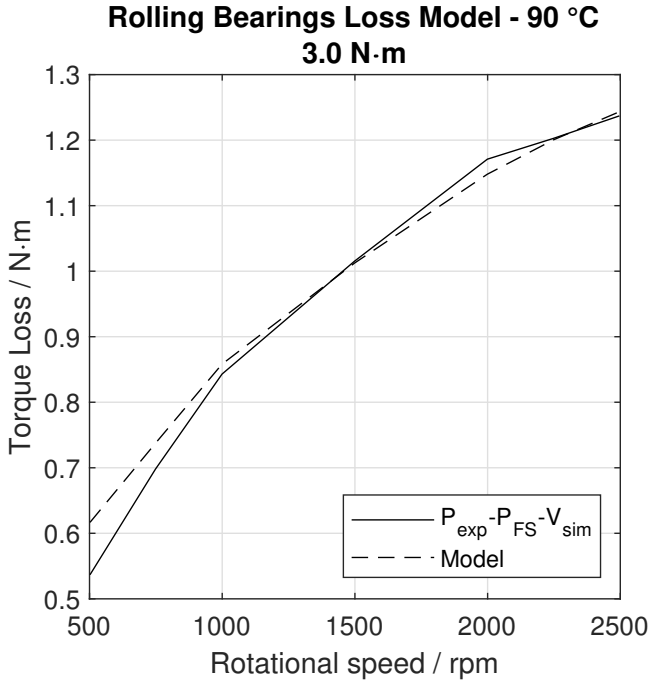
(d) $62.2°C$.



(e) 68.5°*C*.



(f) 77.1°*C*.

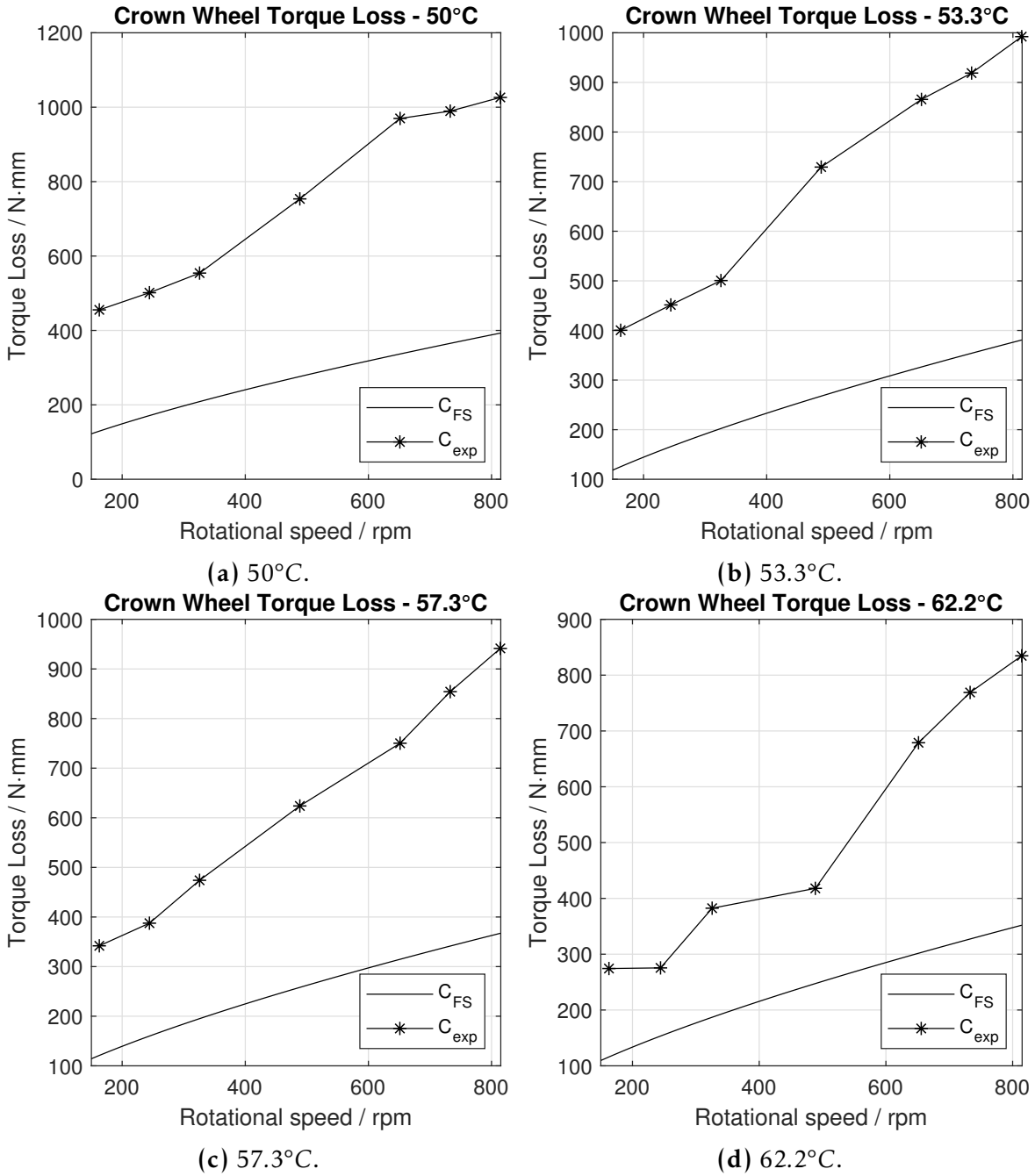


(g) 90°*C*.

Figure A.15: Pinion rolling bearings torque loss model comparison with the experimental results with a starting torque of 3 N·m.

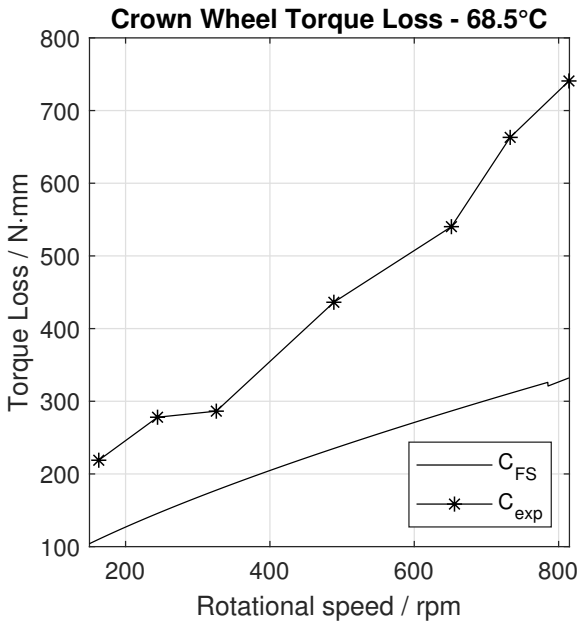
A.4.2 Crown Wheel results

Churning comparison

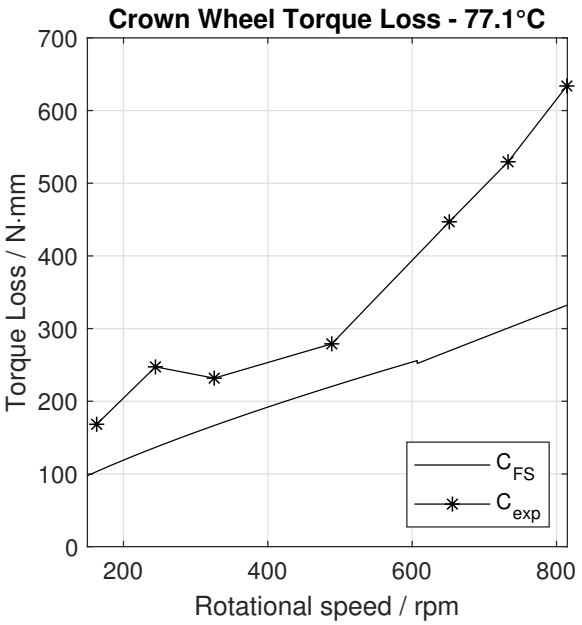


(a) 50°C. **(b)** 53.3°C.

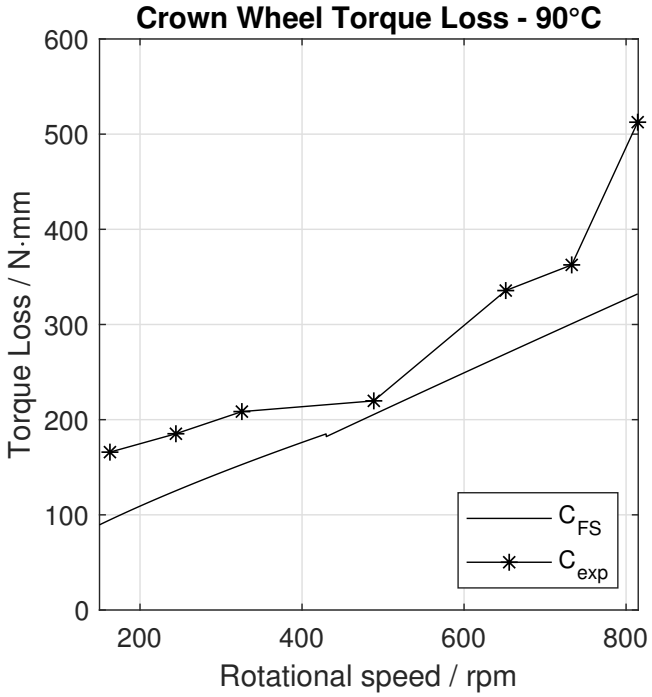
(c) 57.3°C. **(d)** 62.2°C.



(e) 68.5°*C*.



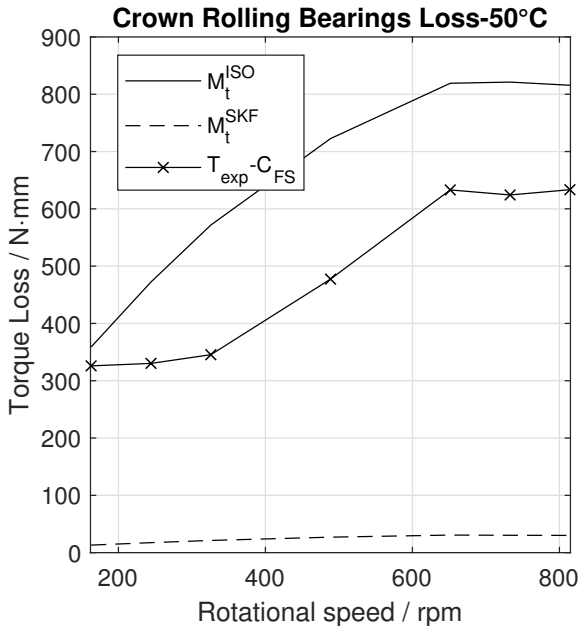
(f) 77.1°*C*.



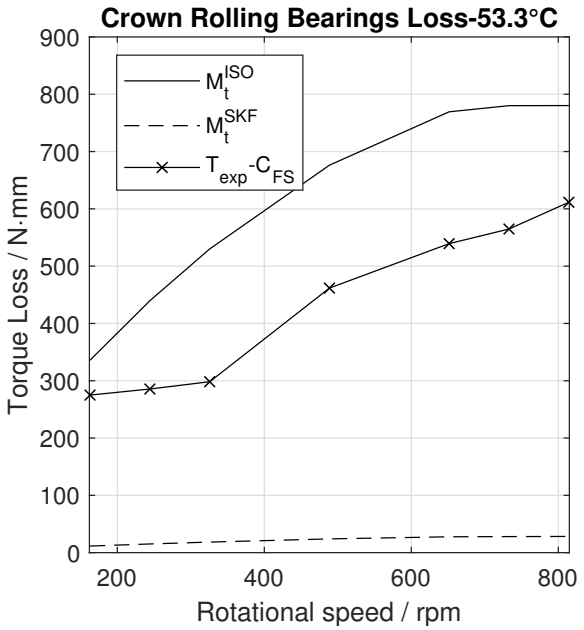
(g) 90°*C*.

Figure A.16: Crown wheel churning torque loss models comparison with the experimental results.

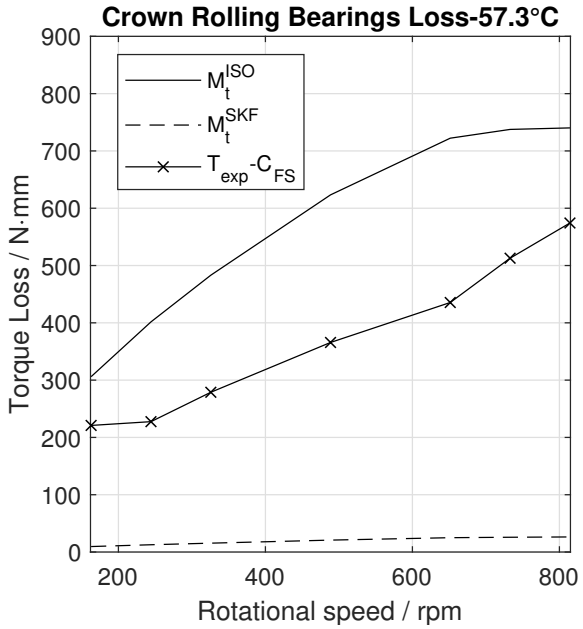
Rolling bearings comparison



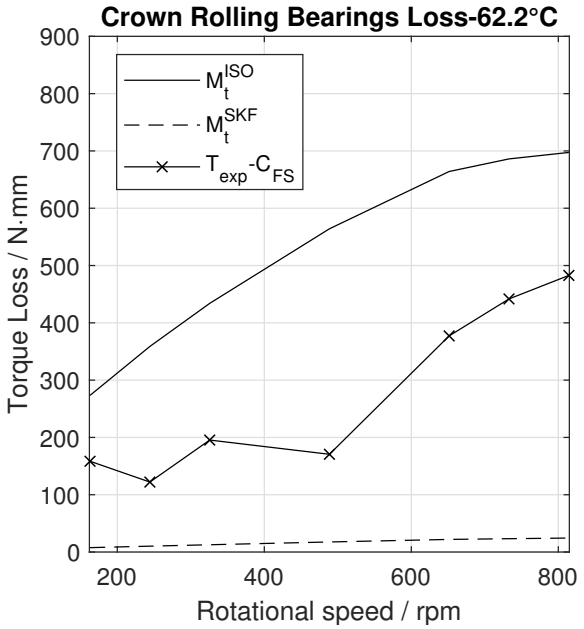
(a) 50°C.



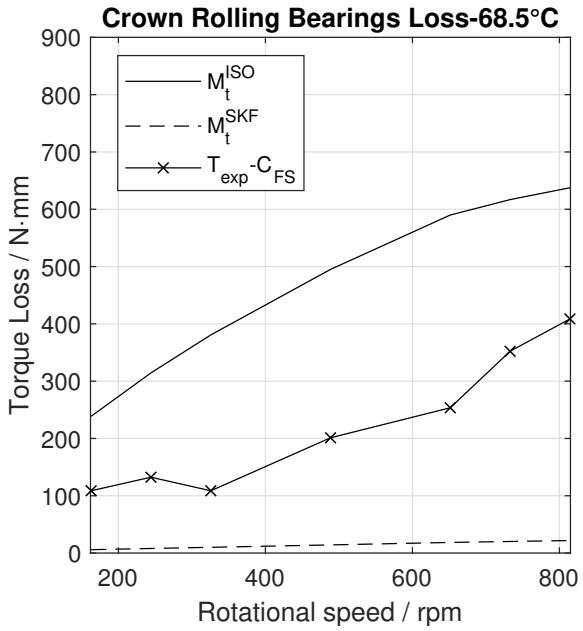
(b) 53.3°C.



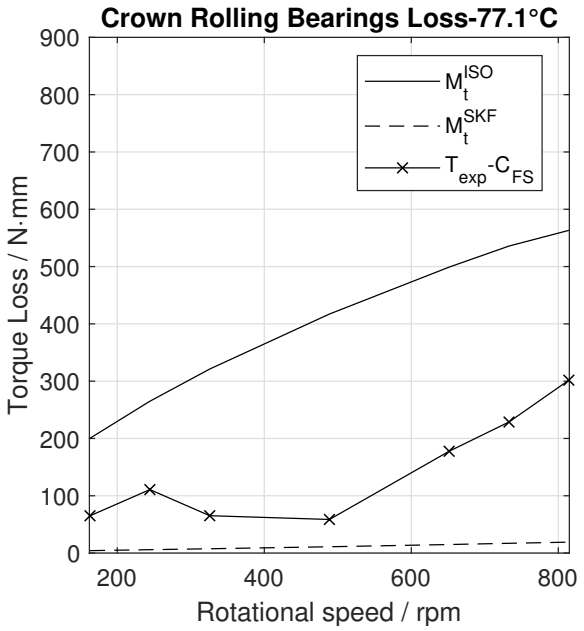
(c) 57.3°C.



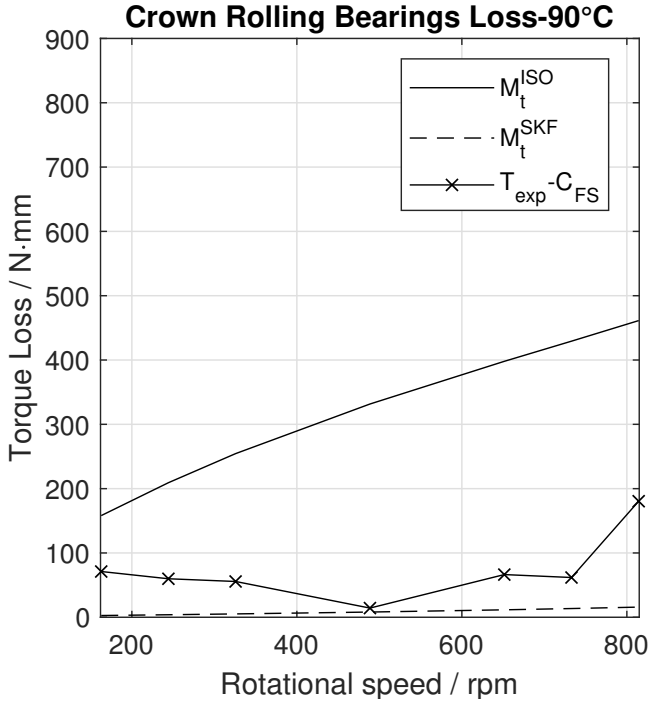
(d) 62.2°C.



(e) 68.5°C.



(f) 77.1°C.



(g) 90°C.

Figure A.17: Crown wheel rolling bearings torque loss models comparison with the experimental results.

B Experimental Datasheets

B.1 Total Power Loss results without the Output Shafts Seals

Table B.1: First experimental results for the complete differential except the shafts seals.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.3	499.3	499.3	499.5	499.1	502.1	500.7
	Torque / N·m	1.38	1.27	1.15	1.02	0.88	0.73	0.58
	Power / W	72.53	66.65	59.89	53.34	45.96	38.58	30.47
	T_{VL} / °C	51.7	54.0	57.5	62.4	68.7	77.2	90.0
	T_{bath} / °C	52.0	54.3	58.0	63.0	69.4	78.1	91.2
750	Speed / rpm	749.4	750.6	749.7	749.6	748.8	749.6	748.9
	Torque / N·m	1.71	1.61	1.46	1.29	1.14	0.97	0.74
	Power / W	133.84	126.35	114.39	101.42	89.78	76.09	58.16
	T_{VL} / °C	51.4	54.2	57.7	62.5	68.3	76.6	89.6
	T_{bath} / °C	51.6	54.3	57.9	62.9	69.0	77.6	90.8
1000	Speed / rpm	1001.1	1002.0	1000.8	1000.2	997.1	999.7	997.6
	Torque / N·m	1.97	1.83	1.69	1.51	1.32	1.11	0.89
	Power / W	206.72	192.14	176.81	158.43	137.90	116.09	93.23
	T_{VL} / °C	51.7	54.4	58.2	62.9	68.7	77.0	89.8
	T_{bath} / °C	51.7	54.4	58.2	63.0	69.0	77.4	90.7
1500	Speed / rpm	1500.0	1501.4	1500.6	1500.7	1498.4	1497.2	1496.3
	Torque / N·m	2.20	2.19	1.98	1.71	1.60	1.38	1.09
	Power / W	346.06	343.71	311.42	269.52	251.09	216.58	170.60
	T_{VL} / °C	53.3	55.5	58.8	63.3	69.2	78.1	90.8
	T_{bath} / °C	53.2	55.5	58.8	63.3	69.3	78.1	91.2
2000	Speed / rpm	2006.3	2002.0	2000.0	2002.4	2001.0	2000.3	2000.3
	Torque / N·m	2.45	2.36	2.18	2.05	1.83	1.59	1.32
	Power / W	515.76	495.68	456.86	429.92	383.41	333.72	276.33
	T_{VL} / °C	56.0	57.8	60.7	64.6	70.2	78.7	91.5
	T_{bath} / °C	56.0	57.9	60.8	64.7	70.2	78.8	91.7
2250	Speed / rpm	2251.1	2252.4	2253.2	2252.0	2249.4	2250.9	2250.4
	Torque / N·m	2.47	2.37	2.27	2.11	1.94	1.69	1.40
	Power / W	581.62	559.33	534.45	498.07	455.79	397.35	328.83
	T_{VL} / °C	59.1	60.7	63.4	66.9	71.6	79.1	91.7
	T_{bath} / °C	59.3	60.9	63.5	67.0	71.7	79.2	91.9
2500	Speed / rpm	2497.6	2502.0	2499.9	2499.6	2498.6	2501.2	2500.2
	Torque / N·m	2.47	2.39	2.34	2.10	2.00	1.83	1.56
	Power / W	645.99	625.53	612.35	548.89	523.45	478.25	407.45
	T_{VL} / °C	62.5	63.9	66.1	69.5	73.6	80.2	91.7
	T_{bath} / °C	62.8	64.1	66.3	69.7	73.6	80.3	91.9

Table B.2: Standard deviation of the first experimental results for the complete differential except the shafts seals.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.8	1.3	1.4	1.3	1.3	1.7	1.4
	Torque / N·m	0.27	0.28	0.29	0.27	0.29	0.28	0.25
	Power / W	13.89	14.69	14.95	14.08	14.90	14.93	13.25
750	Speed / rpm	1.3	1.3	1.3	1.3	1.3	1.4	1.4
	Torque / N·m	0.30	0.32	0.33	0.29	0.30	0.28	0.25
	Power / W	23.82	24.81	25.58	22.46	23.74	21.86	19.63
1000	Speed / rpm	1.4	1.3	1.5	1.1	1.5	1.2	1.9
	Torque / N·m	0.20	0.21	0.22	0.18	0.21	0.21	0.20
	Power / W	20.81	22.33	22.94	19.08	22.27	22.18	20.84
1500	Speed / rpm	1.0	1.2	1.4	1.5	1.2	1.3	1.7
	Torque / N·m	0.21	0.26	0.22	0.30	0.25	0.26	0.26
	Power / W	33.48	40.44	34.21	46.93	38.52	41.15	41.26
2000	Speed / rpm	2.2	1.4	1.0	1.5	1.3	1.1	1.3
	Torque / N·m	0.31	0.31	0.29	0.27	0.28	0.27	0.25
	Power / W	65.17	65.91	61.01	56.63	57.81	55.61	51.71
2250	Speed / rpm	1.3	1.7	1.5	1.4	1.2	1.5	1.3
	Torque / N·m	0.34	0.36	0.33	0.32	0.34	0.29	0.31
	Power / W	80.16	85.53	79.02	74.67	81.19	69.50	73.15
2500	Speed / rpm	1.7	1.5	1.2	1.2	1.7	1.8	1.5
	Torque / N·m	0.40	0.52	0.50	0.48	0.38	0.41	0.46
	Power / W	103.70	137.18	129.82	125.96	99.62	108.05	121.53

Table B.3: Second experimental results for the complete differential except the shafts seals.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	499.8	499.5	499.0	499.0	498.4	499.6	500.4
	Torque / N·m	1.37	1.23	1.12	0.96	0.82	0.68	0.55
	Power / W	71.75	64.28	58.44	50.34	42.73	35.43	28.81
	T_{VL} / °C	50.8	53.8	57.5	62.3	68.5	77.3	90.2
	T_{bath} / °C	51.1	54.1	58.1	62.9	69.2	78.2	91.9
750	Speed / rpm	748.5	750.2	749.5	746.4	746.5	746.1	745.7
	Torque / N·m	1.69	1.54	1.39	1.24	1.07	0.90	0.71
	Power / W	132.57	121.18	109.45	96.74	83.73	70.05	55.43
	T_{VL} / °C	50.9	54.0	57.7	62.4	68.4	76.9	90.0
	T_{bath} / °C	51.1	54.2	58.0	62.9	69.1	77.7	91.4
1000	Speed / rpm	1003.8	1001.6	1000.2	1000.4	999.9	999.5	996.2
	Torque / N·m	1.91	1.76	1.64	1.45	1.30	1.07	0.85
	Power / W	200.32	184.84	172.23	151.85	135.96	112.23	88.64
	T_{VL} / °C	51.2	54.5	58.2	62.8	68.7	77.2	90.1
	T_{bath} / °C	51.2	54.4	58.3	62.9	69.1	77.9	91.0
1500	Speed / rpm	1499.9	1500.9	1499.9	1499.3	1498.4	1496.8	1499.7
	Torque / N·m	2.23	2.13	1.96	1.73	1.57	1.33	0.96
	Power / W	350.24	335.39	307.22	271.14	246.40	209.26	150.43
	T_{VL} / °C	52.5	55.7	59.0	63.3	69.5	78.0	91.0
	T_{bath} / °C	52.5	55.6	59.0	63.4	69.6	78.2	91.3
2000	Speed / rpm	2000.9	1998.2	2001.9	2001.5	2001.0	2000.0	2000.2
	Torque / N·m	2.42	2.27	2.14	2.01	1.77	1.55	1.22
	Power / W	506.82	475.65	447.65	421.24	371.28	324.86	254.66
	T_{VL} / °C	55.2	58.2	60.7	64.5	70.2	78.6	91.5
	T_{bath} / °C	55.2	58.3	60.8	64.5	70.3	78.7	91.8
2250	Speed / rpm	2253.6	2248.5	2253.1	2251.9	2248.6	2250.6	2249.9
	Torque / N·m	2.43	2.28	2.19	2.07	1.90	1.65	1.31
	Power / W	573.47	537.61	517.27	488.28	448.18	388.77	307.63
	T_{VL} / °C	58.1	61.0	63.1	66.4	71.6	79.0	91.8
	T_{bath} / °C	58.4	61.1	63.3	66.6	71.7	79.1	91.9
2500	Speed / rpm	2503.6	2501.4	2502.2	2499.7	2498.8	2498.3	2496.8
	Torque / N·m	2.41	2.33	2.25	2.15	1.99	1.77	1.49
	Power / W	631.64	610.22	589.74	562.02	521.48	462.70	388.99
	T_{VL} / °C	61.6	63.9	66.0	68.9	73.4	80.1	91.8
	T_{bath} / °C	61.8	64.2	66.1	69.1	73.6	80.2	91.9

Table B.4: Standard deviation of the second experimental results for the complete differential except the shafts seals.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.4	1.4	1.2	1.4	1.9	1.4	1.4
	Torque / N·m	0.22	0.26	0.28	0.27	0.27	0.27	0.27
	Power / W	11.30	13.62	14.60	14.17	14.26	13.90	14.10
750	Speed / rpm	1.6	1.3	1.1	1.6	1.6	1.7	1.7
	Torque / N·m	0.24	0.28	0.28	0.28	0.28	0.27	0.25
	Power / W	19.10	21.71	22.23	21.88	21.94	21.22	19.66
1000	Speed / rpm	1.6	1.5	1.1	1.3	1.4	1.1	1.6
	Torque / N·m	0.16	0.18	0.19	0.19	0.18	0.18	0.19
	Power / W	17.27	18.72	20.20	20.16	18.42	19.28	19.30
1500	Speed / rpm	0.8	1.3	1.0	1.5	1.3	1.6	1.4
	Torque / N·m	0.17	0.28	0.28	0.26	0.27	0.26	0.19
	Power / W	26.42	44.59	43.84	40.17	42.93	41.29	30.34
2000	Speed / rpm	1.6	1.3	1.9	1.2	1.7	1.6	1.0
	Torque / N·m	0.25	0.27	0.25	0.27	0.26	0.23	0.24
	Power / W	53.06	56.68	52.57	56.39	54.15	48.96	51.01
2250	Speed / rpm	1.6	1.4	1.5	1.4	1.6	1.2	1.4
	Torque / N·m	0.33	0.33	0.34	0.32	0.30	0.29	0.30
	Power / W	78.33	78.23	79.13	75.73	71.32	68.76	71.83
2500	Speed / rpm	1.7	2.3	1.8	1.4	2.1	1.5	1.5
	Torque / N·m	0.53	0.45	0.47	0.44	0.43	0.43	0.43
	Power / W	139.09	117.02	122.27	113.95	111.77	112.76	113.34

Table B.5: Third experimental results for the complete differential except the shafts seals.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	502.8	496.8	499.6	499.5	499.5	499.8	501.2
	Torque / N·m	1.33	1.22	1.08	0.95	0.81	0.67	0.50
	Power / W	69.93	63.43	56.36	49.76	42.32	35.16	26.37
	T_{VL} / °C	51.1	53.7	57.5	62.4	68.6	77.2	90.3
	T_{bath} / °C	51.4	54.1	58.0	63.0	69.3	78.1	91.7
750	Speed / rpm	749.3	748.3	749.5	750.1	749.7	746.0	748.6
	Torque / N·m	1.65	1.51	1.34	1.07	1.07	0.89	0.68
	Power / W	129.69	118.30	105.32	84.28	84.24	69.56	53.38
	T_{VL} / °C	51.1	53.9	57.8	62.5	68.3	76.8	89.5
	T_{bath} / °C	51.3	54.1	58.0	62.9	69.0	77.7	90.8
1000	Speed / rpm	1000.9	999.8	1001.3	1000.4	999.6	999.4	999.3
	Torque / N·m	1.87	1.70	1.61	1.43	1.26	1.06	0.83
	Power / W	196.09	178.17	168.56	149.66	132.24	110.63	86.49
	T_{VL} / °C	51.2	54.4	58.3	62.9	68.7	77.1	89.9
	T_{bath} / °C	51.2	54.4	58.3	63.0	69.1	77.6	90.6
1500	Speed / rpm	1497.4	1502.1	1494.8	1500.0	1498.5	1499.8	1499.0
	Torque / N·m	2.18	2.06	1.92	1.56	1.56	1.15	1.08
	Power / W	341.10	324.02	300.88	245.67	244.25	181.16	170.09
	T_{VL} / °C	52.8	55.4	59.0	63.3	69.3	78.0	90.6
	T_{bath} / °C	52.7	55.4	59.0	63.3	69.4	78.0	90.8
2000	Speed / rpm	1999.1	2002.0	2001.0	1999.0	2000.8	2000.2	2000.3
	Torque / N·m	2.42	2.26	2.11	1.98	1.76	1.53	1.22
	Power / W	506.07	473.71	441.41	413.60	369.34	319.58	255.32
	T_{VL} / °C	55.2	58.1	61.0	64.6	70.1	78.7	91.2
	T_{bath} / °C	55.3	58.2	61.0	64.7	70.2	78.8	91.5
2250	Speed / rpm	2249.3	2252.8	2250.8	2252.3	2252.2	2250.6	2250.1
	Torque / N·m	2.34	2.27	2.16	2.04	1.85	1.63	1.26
	Power / W	551.49	536.45	509.97	481.82	435.40	383.52	297.65
	T_{VL} / °C	58.2	60.6	63.3	66.6	72.2	79.1	91.5
	T_{bath} / °C	58.4	60.8	63.5	66.7	72.3	79.2	91.7
2500	Speed / rpm	2498.8	2502.5	2497.5	2503.0	2501.3	2498.3	2497.7
	Torque / N·m	2.37	2.29	2.17	2.10	1.91	1.74	1.44
	Power / W	621.10	599.73	567.97	550.35	500.44	455.61	377.53
	T_{VL} / °C	61.3	63.7	67.0	69.1	73.9	80.2	91.3
	T_{bath} / °C	61.6	63.9	67.1	69.2	74.1	80.3	91.4

Table B.6: Standard deviation of the third experimental results for the complete differential except the shafts seals.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.3	1.5	1.3	1.5	1.4	1.1	1.5
	Torque / N·m	0.23	0.28	0.29	0.29	0.27	0.27	0.25
	Power / W	12.23	14.36	14.99	15.32	14.06	14.32	13.06
750	Speed / rpm	1.3	1.4	1.2	1.1	1.3	1.7	1.4
	Torque / N·m	0.26	0.32	0.33	0.33	0.30	0.26	0.25
	Power / W	20.63	25.11	25.87	25.92	23.25	20.70	19.42
1000	Speed / rpm	1.3	1.3	1.4	1.2	1.0	1.3	1.2
	Torque / N·m	0.17	0.20	0.22	0.22	0.20	0.19	0.19
	Power / W	17.41	20.76	22.78	22.55	20.64	19.91	20.32
1500	Speed / rpm	1.5	1.2	1.6	1.3	1.3	1.2	1.4
	Torque / N·m	0.28	0.27	0.27	0.22	0.28	0.17	0.27
	Power / W	43.21	43.03	42.30	35.12	43.52	26.67	42.64
2000	Speed / rpm	1.4	1.6	1.3	1.5	1.4	1.3	1.2
	Torque / N·m	0.28	0.31	0.30	0.31	0.28	0.27	0.27
	Power / W	58.45	64.63	63.66	64.42	58.06	57.42	56.76
2250	Speed / rpm	1.3	1.4	1.4	1.5	1.6	1.3	1.3
	Torque / N·m	0.35	0.35	0.35	0.32	0.31	0.31	0.30
	Power / W	82.25	81.89	81.71	75.80	73.08	72.00	69.75
2500	Speed / rpm	1.3	1.7	1.8	1.5	1.3	1.6	1.6
	Torque / N·m	0.45	0.43	0.41	0.45	0.46	0.46	0.45
	Power / W	117.00	113.31	108.51	117.33	119.71	119.87	118.41

B.2 Pinion and Rolling Bearings Power Loss results

B.2.1 Starting Torque of 0.75 N·m

Table B.7: First experimental results for the pinion and rolling bearings with a starting torque of 0.75 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.5	496.2	499.0	499.5	498.6	500.6	500.8
	Torque / N·m	0.92	0.87	0.80	0.73	0.62	0.53	0.37
	Power / W	47.99	45.20	41.69	38.19	32.44	27.96	19.47
	T_{VL} / °C	50.1	52.0	55.0	58.1	65.3	71.0	82.2
	T_{bath} / °C	49.3	52.9	56.2	61.3	68.8	78.5	91.6
750	Speed / rpm	750.8	748.8	746.6	749.3	750.0	749.8	746.1
	Torque / N·m	1.19	1.16	1.03	0.98	0.84	0.67	0.51
	Power / W	93.29	91.30	80.38	76.61	66.23	52.84	39.92
	T_{VL} / °C	50.1	52.9	55.8	59.1	63.7	70.3	83.3
	T_{bath} / °C	49.8	53.1	56.5	60.5	66.9	76.0	90.4
1000	Speed / rpm	1001.7	998.3	999.8	997.0	996.4	999.6	996.3
	Torque / N·m	1.33	1.29	1.20	1.09	0.99	0.83	0.63
	Power / W	139.58	135.02	125.94	114.11	103.08	87.07	65.60
	T_{VL} / °C	52.6	54.1	57.1	60.3	64.7	71.1	83.1
	T_{bath} / °C	50.6	53.7	57.2	61.8	69.3	77.7	91.3
1500	Speed / rpm	1499.5	1499.3	1498.5	1497.2	1497.5	1495.5	1496.9
	Torque / N·m	1.45	1.42	1.36	1.27	1.15	1.02	0.83
	Power / W	228.10	223.74	213.82	198.69	180.19	159.72	129.48
	T_{VL} / °C	56.3	56.9	59.9	52.8	67.2	72.9	84.7
	T_{bath} / °C	51.0	53.9	58.0	63.1	69.4	78.0	90.7
2000	Speed / rpm	2003.3	2000.9	1999.9	2002.0	1999.0	2001.8	1998.6
	Torque / N·m	1.51	1.47	1.45	1.38	1.27	1.13	0.93
	Power / W	317.72	308.36	304.55	288.29	265.72	237.84	194.95
	T_{VL} / °C	60.2	61.7	63.9	66.2	70.2	75.5	85.5
	T_{bath} / °C	51.5	54.7	58.7	62.9	69.3	77.9	90.7
2250	Speed / rpm	2249.3	2245.4	2247.5	2243.7	2246.4	2249.0	2251.4
	Torque / N·m	1.46	1.44	1.41	1.35	1.26	1.15	0.97
	Power / W	344.81	338.97	331.46	316.14	297.01	271.12	229.61
	T_{VL} / °C	64.8	65.6	67.0	69.7	73.0	77.9	87.0
	T_{bath} / °C	55.2	56.7	59.4	62.6	69.1	78.0	90.7
2500	Speed / rpm	2498.4	2497.8	2497.2	2497.3	2499.4	2502.4	2500.8
	Torque / N·m	1.44	1.43	1.40	1.34	1.27	1.18	1.01
	Power / W	376.21	373.85	366.89	349.82	331.51	308.09	264.91
	T_{VL} / °C	69.1	68.7	70.3	72.7	75.4	80.0	88.5
	T_{bath} / °C	58.5	58.9	61.0	64.7	69.8	78.0	90.7

Table B.8: Standard deviation of the first experimental results for the pinion and rolling bearings with a starting torque of 0.75 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.6	1.6	1.5	1.5	1.9	1.5	1.4
	Torque / N·m	0.20	0.26	0.27	0.26	0.25	0.20	0.24
	Power / W	10.54	13.73	14.34	13.83	13.08	10.47	12.43
750	Speed / rpm	1.4	1.7	1.6	1.3	1.1	1.5	1.7
	Torque / N·m	0.20	0.31	0.29	0.25	0.22	0.18	0.22
	Power / W	16.06	24.12	23.05	19.57	17.05	13.77	17.17
1000	Speed / rpm	1.4	1.3	2.2	1.4	1.8	1.1	1.5
	Torque / N·m	0.15	0.19	0.20	0.16	0.18	0.16	0.18
	Power / W	15.24	20.33	20.65	17.01	19.00	17.19	19.03
1500	Speed / rpm	1.3	1.5	1.3	1.5	1.4	2.2	1.5
	Torque / N·m	0.19	0.17	0.20	0.19	0.20	0.19	0.20
	Power / W	30.45	26.08	32.03	29.34	30.67	29.12	31.26
2000	Speed / rpm	1.5	1.3	1.3	1.7	1.5	1.4	1.3
	Torque / N·m	0.27	0.27	0.33	0.26	0.29	0.25	0.25
	Power / W	56.55	56.17	69.56	53.62	61.33	52.42	51.33
2250	Speed / rpm	1.3	1.7	1.3	1.6	1.6	1.2	1.8
	Torque / N·m	0.36	0.32	0.30	0.32	0.32	0.32	0.32
	Power / W	83.64	76.16	69.47	75.57	75.15	76.44	76.54
2500	Speed / rpm	1.2	1.7	1.4	1.4	1.2	1.4	1.1
	Torque / N·m	0.46	0.44	0.43	0.47	0.42	0.47	0.46
	Power / W	119.66	114.51	111.59	122.92	108.95	123.65	119.80

Table B.9: Second experimental results for the pinion and rolling bearings with a starting torque of 0.75 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.4	500.1	499.6	498.6	496.2	499.9	494.7
	Torque / N·m	1.03	0.90	0.81	0.74	0.64	0.56	0.41
	Power / W	53.95	47.36	42.50	38.54	33.27	29.15	21.32
	T_{VL} / °C	46.8	51.3	55.1	58.3	63.1	71.3	79.2
	T_{bath} / °C	48.7	52.0	56.1	61.3	67.6	77.1	89.5
750	Speed / rpm	749.0	748.1	747.7	747.1	747.4	746.4	745.4
	Torque / N·m	1.29	1.16	1.06	0.95	0.84	0.71	0.54
	Power / W	100.90	90.73	82.66	74.42	65.61	55.35	42.51
	T_{VL} / °C	48.3	52.1	55.4	59.2	63.7	70.7	83.1
	T_{bath} / °C	49.1	52.2	56.5	60.7	67.4	74.7	91
1000	Speed / rpm	999.9	1000.0	1000.5	1000.5	999.9	998.9	999.4
	Torque / N·m	1.49	1.30	1.22	1.13	1.05	0.85	0.66
	Power / W	155.75	136.13	127.65	118.04	110.17	88.79	68.57
	T_{VL} / °C	50.0	53.6	56.6	59.9	64.5	71.3	83.0
	T_{bath} / °C	50.3	53.5	57.1	60.9	69.4	78.0	91.1
1500	Speed / rpm	1497.8	1495.3	1496.2	1494.9	1497.6	1496.7	1496.3
	Torque / N·m	1.51	1.42	1.36	1.26	1.15	1.02	0.84
	Power / W	236.59	222.29	213.01	197.19	179.62	159.42	131.00
	T_{VL} / °C	52.8	56.3	59.9	62.1	66.7	73.0	84.2
	T_{bath} / °C	48.3	53.2	57.7	62.8	69.5	77.6	90.3
2000	Speed / rpm	2006.0	2002.8	2002.1	2001.2	2001.0	2000.6	1997.5
	Torque / N·m	1.61	1.49	1.44	1.36	1.27	1.12	0.94
	Power / W	337.48	313.12	301.08	285.58	267.12	234.15	197.42
	T_{VL} / °C	56.5	60.5	62.4	65.3	69.6	75.7	85.7
	T_{bath} / °C	49.1	53.5	57.9	63.0	69.3	77.8	90.8
2250	Speed / rpm	2255.5	2252.8	2251.8	2248.9	2251.0	2249.9	2250.7
	Torque / N·m	1.58	1.48	1.44	1.37	1.29	1.13	0.99
	Power / W	372.54	350.26	339.53	322.72	304.56	267.41	233.60
	T_{VL} / °C	60.7	63.5	65.4	68.6	72.5	78.0	87.4
	T_{bath} / °C	51.3	54.7	58.4	63.4	69.4	78.0	90.9
2500	Speed / rpm	2505.6	2496.7	2498.1	2499.8	2498.1	2497.0	2499.5
	Torque / N·m	1.55	1.49	1.45	1.37	1.29	1.18	1.00
	Power / W	405.61	388.63	378.72	357.35	338.29	309.52	262.91
	T_{VL} / °C	64.0	66.9	68.6	71.3	75.2	80.2	87.1
	T_{bath} / °C	54.5	57.4	59.9	63.8	69.4	77.8	90.7

Table B.10: Standard deviation of the second experimental results for the pinion and rolling bearings with a starting torque of 0.75 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.6	1.7	1.6	2.2	1.6	1.3	1.5
	Torque / N·m	0.19	0.24	0.26	0.26	0.25	0.26	0.25
	Power / W	10.08	12.35	13.65	13.57	13.07	13.43	13.00
750	Speed / rpm	1.3	1.4	1.4	1.5	1.3	1.6	1.7
	Torque / N·m	0.21	0.26	0.26	0.27	0.28	0.26	0.25
	Power / W	16.20	20.48	20.16	21.40	21.70	19.93	19.23
1000	Speed / rpm	1.4	1.8	1.7	1.4	0.7	1.3	1.2
	Torque / N·m	0.20	0.18	0.19	0.19	0.20	0.19	0.19
	Power / W	21.01	18.57	19.90	19.84	20.73	19.68	19.68
1500	Speed / rpm	1.5	2.5	1.6	1.7	1.4	1.6	1.7
	Torque / N·m	0.20	0.20	0.20	0.20	0.20	0.19	0.20
	Power / W	31.73	30.74	30.94	31.14	32.04	30.56	31.91
2000	Speed / rpm	1.8	1.7	1.5	1.1	1.3	1.2	1.3
	Torque / N·m	0.24	0.25	0.27	0.27	0.28	0.23	0.24
	Power / W	50.49	53.29	57.38	55.97	59.64	49.16	50.94
2250	Speed / rpm	1.6	1.5	1.4	1.1	1.2	1.3	1.2
	Torque / N·m	0.33	0.34	0.32	0.31	0.32	0.28	0.30
	Power / W	78.44	79.57	75.32	73.81	75.33	65.05	71.64
2500	Speed / rpm	1.6	1.6	1.4	1.7	1.4	1.6	1.4
	Torque / N·m	0.54	0.49	0.47	0.43	0.45	0.40	0.40
	Power / W	141.43	127.51	121.91	112.69	116.80	105.59	104.95

Table B.11: Third experimental results for the pinion and rolling bearings with a starting torque of 0.75 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.4	496.8	499.7	499.6	499.6	497.6	500.1
	Torque / N·m	0.98	0.85	0.78	0.71	0.63	0.53	0.39
	Power / W	51.36	44.41	40.70	37.20	32.78	27.40	20.26
	T_{VL} / °C	48.3	52.9	55.6	59.2	64.1	70.7	80.3
	T_{bath} / °C	49.3	52.7	56.4	61.6	67.8	75.3	90.6
750	Speed / rpm	751.1	748.0	749.9	747.4	748.8	749.4	749.0
	Torque / N·m	1.26	1.11	1.02	0.95	0.86	0.70	0.53
	Power / W	98.84	87.27	80.24	74.26	67.34	54.99	41.48
	T_{VL} / °C	49.2	53.3	56.2	59.8	64.1	71.3	83.3
	T_{bath} / °C	48.3	52.7	56.6	61.6	68.3	76.1	90.9
1000	Speed / rpm	1002.2	1000.6	999.1	998.6	996.8	998.7	999.0
	Torque / N·m	1.38	1.26	1.18	1.08	0.97	0.85	0.65
	Power / W	144.86	132.23	123.67	113.10	101.52	88.59	67.55
	T_{VL} / °C	50.6	54.4	57.1	60.7	65.1	71.8	83.2
	T_{bath} / °C	50.0	53.5	56.8	61.4	69.4	78.0	90.8
1500	Speed / rpm	1500.4	1499.7	1497.9	1497.8	1497.7	1496.8	1498.8
	Torque / N·m	1.49	1.49	1.32	1.25	1.12	1.01	0.83
	Power / W	233.33	234.51	207.32	195.87	175.72	157.66	130.79
	T_{VL} / °C	53.2	56.7	59.2	62.7	67.6	73.6	84.6
	T_{bath} / °C	49.1	52.3	58.0	62.8	69.6	78.0	90.6
2000	Speed / rpm	2001.4	2002.3	1999.1	2001.4	2000.1	2000.2	1999.5
	Torque / N·m	1.51	1.46	1.41	1.33	1.24	1.12	0.91
	Power / W	316.19	306.69	294.87	279.47	260.45	233.76	190.40
	T_{VL} / °C	56.6	59.7	62.7	65.8	70.3	76.4	86.2
	T_{bath} / °C	50.7	53.9	57.9	63.2	69.4	78.0	91.0
2250	Speed / rpm	2251.4	2250.0	2251.1	2250.9	2251.0	2249.6	2250.2
	Torque / N·m	1.50	1.44	1.41	1.35	1.25	1.13	0.95
	Power / W	352.86	340.18	332.94	319.11	295.81	267.06	224.65
	T_{VL} / °C	60.1	63.4	65.8	69.1	73.4	78.9	88.0
	T_{bath} / °C	52.1	55.2	59.2	63.5	69.6	78.0	90.7
2500	Speed / rpm	2501.4	2498.9	2498.5	2500.0	2500.0	2500.0	2499.7
	Torque / N·m	1.52	1.47	1.43	1.31	1.27	1.17	0.98
	Power / W	398.48	384.40	374.06	343.35	332.09	306.90	255.48
	T_{VL} / °C	64.3	66.8	69.3	72.1	76.3	81.2	89.7
	T_{bath} / °C	54.8	57.3	60.9	64.3	69.8	78.1	90.8

Table B.12: Standard deviation of the third experimental results for the pinion and rolling bearings with a starting torque of 0.75 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.5	1.7	1.6	1.4	1.5	1.4	2.0
	Torque / N·m	0.21	0.25	0.26	0.26	0.26	0.26	0.26
	Power / W	10.81	13.09	13.67	13.47	13.84	13.50	13.36
750	Speed / rpm	1.4	1.4	1.6	1.4	2.2	1.4	1.4
	Torque / N·m	0.21	0.26	0.29	0.27	0.27	0.25	0.24
	Power / W	16.85	20.60	22.85	20.91	20.99	19.85	18.89
1000	Speed / rpm	1.2	1.8	1.9	1.8	1.5	1.4	1.4
	Torque / N·m	0.17	0.19	0.18	0.19	0.20	0.20	0.20
	Power / W	18.10	19.43	19.27	19.49	20.60	20.72	20.81
1500	Speed / rpm	1.0	1.0	1.3	1.3	1.5	1.6	1.2
	Torque / N·m	0.24	0.24	0.20	0.20	0.20	0.22	0.21
	Power / W	37.80	37.55	31.41	31.73	31.55	34.84	32.72
2000	Speed / rpm	1.3	1.6	1.5	1.3	1.1	1.3	1.2
	Torque / N·m	0.26	0.27	0.28	0.26	0.23	0.26	0.23
	Power / W	53.48	55.56	59.22	54.76	47.30	53.75	47.48
2250	Speed / rpm	1.5	1.8	1.4	1.0	1.2	1.2	1.4
	Torque / N·m	0.33	0.31	0.31	0.31	0.29	0.27	0.26
	Power / W	77.77	72.12	73.25	74.18	68.62	63.39	60.84
2500	Speed / rpm	1.1	1.6	2.1	1.3	1.2	2.3	1.1
	Torque / N·m	0.50	0.48	0.48	0.44	0.46	0.45	0.42
	Power / W	132.00	125.07	124.36	115.21	119.62	118.85	110.66

B.2.2 Starting Torque of 1.9 N·m

Table B.13: First experimental results for the pinion and rolling bearings with a starting torque of 1.9 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.0	497.4	499.4	501.6	495.7	496.9	500.5
	Torque / N·m	1.23	1.15	1.02	0.90	0.77	0.64	0.52
	Power / W	64.26	59.66	53.51	47.07	39.84	33.45	27.22
	T_{VL} / °C	50.5	54.2	58.1	62.8	68.8	77.6	89.8
	T_{bath} / °C	50.6	53.4	57.8	62.5	68.9	78.3	91.5
750	Speed / rpm	751.0	747.3	746.2	748.6	746.4	748.4	748.0
	Torque / N·m	1.51	1.40	1.27	1.11	1.00	0.86	0.66
	Power / W	118.82	109.49	98.89	87.21	78.09	67.55	51.97
	T_{VL} / °C	51.6	54.6	58.6	62.8	68.8	77.5	90.2
	T_{bath} / °C	49.8	53.6	58.0	63.1	69.5	78.2	91.0
1000	Speed / rpm	1002.4	1000.9	998.2	998.6	998.5	1001.8	995.7
	Torque / N·m	1.67	1.55	1.43	1.30	1.18	1.00	0.81
	Power / W	175.72	162.50	149.82	135.56	123.28	105.20	84.31
	T_{VL} / °C	52.4	55.6	59.6	63.6	69.1	77.3	89.3
	T_{bath} / °C	50.8	54.2	57.5	63.2	69.4	78.0	91.0
1500	Speed / rpm	1501.4	1502.9	1498.2	1500.0	1499.4	1498.6	1497.5
	Torque / N·m	1.82	1.73	1.59	1.50	1.35	1.21	1.02
	Power / W	285.47	272.85	249.33	235.76	212.60	189.18	159.50
	T_{VL} / °C	56.9	59.4	63.1	66.1	70.5	77.8	90.5
	T_{bath} / °C	51.3	54.7	58.0	63.3	69.8	78.0	91.1
2000	Speed / rpm	2001.1	1997.8	1998.9	1998.3	1996.7	1999.3	1996.8
	Torque / N·m	1.87	1.79	1.67	1.60	1.50	1.32	1.12
	Power / W	392.03	373.87	350.57	334.19	312.81	277.04	233.75
	T_{VL} / °C	61.0	53.9	66.8	68.9	73.3	79.5	90.6
	T_{bath} / °C	50.8	54.2	57.5	63.2	69.4	78.0	91.0
2250	Speed / rpm	2250.6	2251.1	2252.7	2248.3	2247.8	2253.0	2247.6
	Torque / N·m	1.79	1.72	1.63	1.58	1.47	1.35	1.17
	Power / W	422.20	404.79	384.33	371.69	345.28	317.75	274.41
	T_{VL} / °C	65.0	67.6	70.6	72.0	76.6	81.5	91.0
	T_{bath} / °C	49.8	53.6	58.0	63.1	69.5	78.2	91.0
2500	Speed / rpm	2501.3	2498.0	2499.7	2498.0	2496.6	2499.5	2500.5
	Torque / N·m	1.75	1.69	1.67	1.58	1.48	1.39	1.20
	Power / W	459.39	442.60	436.59	412.28	387.25	363.39	313.55
	T_{VL} / °C	68.7	71.3	72.8	75.2	78.9	83.4	92.3
	T_{bath} / °C	50.6	53.4	57.8	62.5	68.9	78.3	91.5

Table B.14: Standard deviation of the first experimental results for the pinion and rolling bearings with a starting torque of 1.9 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1,1	1,9	1,6	1,5	1,6	1,3	1,6
	Torque / N·m	0,21	0,28	0,29	0,29	0,29	0,28	0,27
	Power / W	11,07	14,52	15,24	15,46	14,98	14,57	14,21
750	Speed / rpm	1,5	1,4	1,7	1,5	1,6	1,3	1,3
	Torque / N·m	0,27	0,31	0,31	0,31	0,34	0,32	0,31
	Power / W	20,89	24,01	24,08	24,14	26,68	24,71	23,92
1000	Speed / rpm	1,6	1,2	2,3	1,3	1,3	1,2	2,2
	Torque / N·m	0,17	0,19	0,19	0,21	0,22	0,20	0,19
	Power / W	18,30	20,28	19,97	21,47	22,74	21,46	20,00
1500	Speed / rpm	1,1	1,4	1,3	1,1	1,4	1,2	1,5
	Torque / N·m	0,20	0,21	0,22	0,14	0,20	0,19	0,21
	Power / W	31,19	32,63	33,85	21,21	31,26	29,46	32,30
2000	Speed / rpm	1,4	1,4	1,3	1,4	2,0	1,5	1,5
	Torque / N·m	0,24	0,30	0,29	0,27	0,31	0,25	0,28
	Power / W	51,27	62,25	61,13	56,91	65,09	51,69	58,69
2250	Speed / rpm	1,4	1,5	1,6	1,4	1,3	1,5	1,4
	Torque / N·m	0,36	0,34	0,35	0,31	0,25	0,25	0,26
	Power / W	85,87	81,14	82,12	72,62	58,73	58,87	61,35
2500	Speed / rpm	1,6	1,4	1,4	2,0	1,6	1,2	1,5
	Torque / N·m	0,45	0,44	0,40	0,37	0,37	0,37	0,37
	Power / W	117,95	115,37	104,14	97,19	96,57	96,85	97,45

Table B.15: Second experimental results for the pinion and rolling bearings with a starting torque of 1.9 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	499.7	499.6	499.3	499.0	501.7	499.8	500.4
	Torque / N·m	1.23	1.16	1.04	0.92	0.80	0.67	0.54
	Power / W	64.35	60.88	54.25	48.14	42.16	35.23	28.13
	T_{VL} / °C	50.5	54.0	57.9	62.7	68.8	77.2	89.6
	T_{bath} / °C	50.4	53.6	57.3	63.0	69.2	78.1	91.4
750	Speed / rpm	747.9	749.2	747.6	746.1	746.5	749.1	745.4
	Torque / N·m	1.52	1.51	1.28	1.16	1.04	0.87	0.69
	Power / W	119.31	118.68	100.27	90.94	81.44	68.22	53.71
	T_{VL} / °C	51.5	54.2	58.0	62.4	68.4	77.1	90.2
	T_{bath} / °C	50.0	53.5	57.9	63.1	69.4	78.0	90.8
1000	Speed / rpm	1002.9	1000.5	1000.4	996.2	996.5	1001.8	998.4
	Torque / N·m	1.69	1.57	1.46	1.33	1.21	1.03	0.83
	Power / W	177.21	164.33	153.31	138.64	126.13	107.87	86.44
	T_{VL} / °C	52.4	55.3	58.5	63.0	68.9	76.9	89.2
	T_{bath} / °C	50.8	54.2	57.5	63.1	69.3	78.0	91.4
1500	Speed / rpm	1501.0	1496.3	1495.5	1498.0	1500.1	1499.2	1498.5
	Torque / N·m	1.79	1.71	1.65	1.52	1.36	1.24	1.04
	Power / W	281.94	268.43	258.96	238.55	213.43	195.10	162.42
	T_{VL} / °C	57.6	59.1	61.5	65.5	69.8	77.4	90.3
	T_{bath} / °C	51.5	54.7	58.1	63.3	69.7	78.0	91.2
2000	Speed / rpm	1997.8	1997.8	2000.0	1999.4	1998.6	1996.8	1998.0
	Torque / N·m	1.88	1.75	1.73	1.62	1.51	1.34	1.17
	Power / W	393.98	365.65	362.63	339.38	316.09	280.35	244.18
	T_{VL} / °C	60.6	63.7	65.7	68.6	72.8	78.8	90.4
	T_{bath} / °C	52.9	56.5	59.5	63.7	69.8	78.2	91.1
2250	Speed / rpm	2250.5	2251.8	2250.5	2249.1	2251.3	2248.7	2249.2
	Torque / N·m	1.80	1.69	1.67	1.61	1.51	1.38	1.20
	Power / W	424.45	399.70	393.31	378.44	355.66	324.36	281.56
	T_{VL} / °C	64.2	68.1	69.4	71.4	75.4	80.8	90.7
	T_{bath} / °C	55.3	59.0	61.2	64.9	70.3	78.3	91.0
2500	Speed / rpm	2500.8	2498.8	2497.9	2496.3	2495.3	2498.9	2500.6
	Torque / N·m	1.77	1.68	1.65	1.60	1.52	1.41	1.23
	Power / W	463.92	438.98	432.47	418.91	398.35	368.41	322.22
	T_{VL} / °C	68.3	70.7	72.1	74.0	77.8	82.7	91.7
	T_{bath} / °C	57.9	61.3	63.6	66.6	71.3	78.4	91.1

Table B.16: Standard deviation of the second experimental results for the pinion and rolling bearings with a starting torque of 1.9 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.5	1.5	1.6	1.8	2.1	1.4	1.5
	Torque / N·m	0.29	0.31	0.31	0.29	0.30	0.27	0.27
	Power / W	15.33	16.39	16.00	14.93	15.58	14.05	13.90
750	Speed / rpm	1.4	1.6	2.0	1.7	1.7	1.2	1.7
	Torque / N·m	0.35	0.30	0.32	0.29	0.30	0.26	0.26
	Power / W	27.15	23.89	25.24	22.30	23.25	20.75	20.65
1000	Speed / rpm	1.4	1.1	1.1	1.6	1.5	1.2	1.2
	Torque / N·m	0.20	0.19	0.18	0.17	0.19	0.16	0.16
	Power / W	20.57	19.39	18.97	17.98	19.56	16.46	16.65
1500	Speed / rpm	1.3	1.6	1.6	1.6	1.2	1.1	1.5
	Torque / N·m	0.19	0.19	0.19	0.19	0.13	0.21	0.19
	Power / W	29.91	29.61	30.38	29.63	20.51	32.56	29.86
2000	Speed / rpm	1.6	1.4	1.3	1.2	1.4	1.9	1.4
	Torque / N·m	0.28	0.27	0.24	0.26	0.27	0.24	0.25
	Power / W	59.44	57.47	50.09	54.53	57.40	49.88	53.15
2250	Speed / rpm	1.3	1.4	1.6	1.4	1.2	1.4	1.3
	Torque / N·m	0.31	0.31	0.28	0.30	0.28	0.30	0.29
	Power / W	72.40	73.84	65.10	69.88	67.13	70.31	68.96
2500	Speed / rpm	1.5	1.3	1.7	1.8	1.7	1.2	2.3
	Torque / N·m	0.39	0.39	0.39	0.36	0.35	0.36	0.35
	Power / W	101.76	101.69	102.42	93.26	90.97	93.57	92.77

Table B.17: Third experimental results for the pinion and rolling bearings with a starting torque of 1.9 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	498.7	498.6	498.8	495.5	502.1	499.4	503.1
	Torque / N·m	1.23	1.12	1.01	0.89	0.77	0.65	0.53
	Power / W	64.25	58.59	52.91	46.42	40.33	34.09	27.79
	T_{VL} / °C	50.3	54.2	57.7	62.6	68.8	77.6	89.7
	T_{bath} / °C	50.5	53.6	57.7	62.8	69.0	78.5	91.8
750	Speed / rpm	747.1	747.0	746.2	747.3	749.6	745.6	751.7
	Torque / N·m	1.48	1.36	1.27	1.15	1.00	0.84	0.68
	Power / W	115.99	106.33	98.87	89.98	78.73	65.91	53.92
	T_{VL} / °C	51.7	54.6	58.2	62.7	68.6	77.6	90.3
	T_{bath} / °C	50.4	53.8	58.1	63.2	69.2	78.3	91.1
1000	Speed / rpm	1001.5	1000.2	1000.4	996.2	998.6	998.4	998.1
	Torque / N·m	1.64	1.53	1.46	1.31	1.19	1.00	0.81
	Power / W	172.28	160.07	152.42	137.01	124.00	104.44	85.14
	T_{VL} / °C	52.5	56.0	59.1	63.1	68.9	77.3	89.4
	T_{bath} / °C	51.2	54.6	57.8	63.0	69.3	78.3	91.6
1500	Speed / rpm	1502.9	1499.6	1501.3	1500.3	1499.8	1498.9	1498.2
	Torque / N·m	1.78	1.66	1.56	1.56	1.36	1.25	1.02
	Power / W	279.50	260.01	244.65	245.21	213.43	195.67	159.82
	T_{VL} / °C	57.2	59.8	63.5	65.9	70.4	77.6	90.6
	T_{bath} / °C	51.4	55.0	58.7	63.1	69.7	78.0	91.4
2000	Speed / rpm	1999.1	1996.8	1998.6	1999.2	2001.1	1998.0	2001.5
	Torque / N·m	1.85	1.75	1.65	1.58	1.49	1.35	1.15
	Power / W	388.31	366.53	345.87	331.56	312.63	283.18	241.26
	T_{VL} / °C	61.3	64.0	67.3	69.1	73.5	78.8	90.5
	T_{bath} / °C	53.4	56.7	60.5	64.2	70.0	78.2	90.9
2250	Speed / rpm	2252.4	2250.4	2252.4	2246.3	2250.9	2247.7	2248.5
	Torque / N·m	1.75	1.68	1.63	1.58	1.52	1.37	1.19
	Power / W	413.67	397.04	384.66	370.74	359.33	322.59	279.75
	T_{VL} / °C	65.1	68.0	70.3	72.2	75.0	81.2	90.9
	T_{bath} / °C	55.9	59.2	62.5	65.8	70.3	78.3	91.2
2500	Speed / rpm	2498.7	2500.4	2495.4	2501.8	2497.3	2500.2	2497.6
	Torque / N·m	1.72	1.72	1.62	1.57	1.51	1.39	1.23
	Power / W	450.07	449.20	422.43	411.37	395.36	364.67	321.60
	T_{VL} / °C	69.7	71.3	73.3	75.1	78.0	83.0	91.2
	T_{bath} / °C	59.2	61.8	65.0	68.0	71.8	78.5	90.1

Table B.18: Standard deviation of the third experimental results for the pinion and rolling bearings with a starting torque of 1.9 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.3	1.6	1.5	1.6	1.5	1.7	1.5
	Torque / N·m	0.31	0.29	0.31	0.29	0.29	0.28	0.28
	Power / W	15.97	14.96	15.95	15.13	15.32	14.85	14.88
750	Speed / rpm	1.4	1.5	1.6	2.2	1.8	1.8	1.3
	Torque / N·m	0.33	0.32	0.31	0.31	0.31	0.28	0.27
	Power / W	25.82	25.14	24.22	24.37	24.50	21.67	21.23
1000	Speed / rpm	1.4	1.0	1.1	1.8	1.2	1.2	1.3
	Torque / N·m	0.19	0.20	0.20	0.19	0.18	0.18	0.18
	Power / W	20.06	20.45	20.72	20.07	19.33	18.71	18.52
1500	Speed / rpm	1.5	1.2	1.5	1.0	1.3	1.1	1.4
	Torque / N·m	0.20	0.18	0.20	0.21	0.21	0.19	0.18
	Power / W	31.14	28.77	31.16	33.16	33.16	29.31	28.67
2000	Speed / rpm	1.8	1.7	1.4	1.8	1.2	1.3	2.0
	Torque / N·m	0.30	0.29	0.28	0.25	0.24	0.22	0.21
	Power / W	63.86	60.15	58.05	52.24	50.63	45.76	43.23
2250	Speed / rpm	1.4	1.3	1.3	1.8	1.4	1.5	1.3
	Torque / N·m	0.33	0.33	0.31	0.30	0.30	0.30	0.28
	Power / W	76.70	76.76	73.70	70.34	69.57	71.43	65.94
2500	Speed / rpm	1.3	1.2	1.9	1.5	1.4	1.3	1.4
	Torque / N·m	0.40	0.42	0.38	0.36	0.38	0.33	0.34
	Power / W	105.50	108.88	98.77	93.76	99.35	87.07	90.07

B.2.3 Starting Torque of 3 N·m

Table B.19: First experimental results for the pinion and rolling bearings with a starting torque of 3 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	499.5	496.9	498.3	499.1	499.0	499.4	502.7
	Torque / N·m	1.29	1.19	1.08	0.97	0.83	0.70	0.57
	Power / W	67.41	61.80	56.35	50.69	43.20	36.67	30.22
	T_{VL} / °C	51.1	54.1	58.1	62.7	69.0	77.5	89.7
	T_{bath} / °C	50.6	53.7	57.4	63.5	69.2	78.3	91.5
750	Speed / rpm	747.9	750.9	749.2	750.1	749.0	751.8	749.0
	Torque / N·m	1.57	1.35	1.34	1.27	1.07	0.93	0.72
	Power / W	122.98	106.04	105.32	99.50	84.08	73.31	56.69
	T_{VL} / °C	52.4	54.6	58.6	62.4	68.5	77.2	90.1
	T_{bath} / °C	50.5	53.4	57.8	63.3	69.3	78.1	90.4
1000	Speed / rpm	1002.4	1001.3	1000.2	1000.3	1003.0	999.6	1001.6
	Torque / N·m	1.76	1.64	1.51	1.39	1.27	1.09	0.87
	Power / W	184.35	172.48	158.50	146.04	133.71	114.00	91.52
	T_{VL} / °C	53.1	55.4	59.3	63.1	69.0	77.1	88.8
	T_{bath} / °C	51.1	54.1	57.5	62.8	69.3	78.2	91.7
1500	Speed / rpm	1501.5	1503.2	1502.3	1502.0	1500.6	1499.6	1499.5
	Torque / N·m	1.94	1.82	1.71	1.61	1.48	1.38	1.04
	Power / W	304.60	286.89	269.19	253.19	232.54	217.22	163.99
	T_{VL} / °C	57.2	59.6	62.9	65.7	70.1	77.4	89.9
	T_{bath} / °C	51.3	54.5	58.4	63.0	69.5	78.0	91.4
2000	Speed / rpm	2001.6	1999.2	1997.4	1999.5	1999.0	1998.8	1999.3
	Torque / N·m	1.92	1.88	1.76	1.58	1.61	1.43	1.23
	Power / W	402.88	392.91	368.62	330.49	336.55	300.27	256.72
	T_{VL} / °C	61.5	63.5	67.2	69.1	73.1	79.0	90.4
	T_{bath} / °C	53.4	55.9	60.0	63.7	69.8	78.1	91.1
2250	Speed / rpm	2254.3	2252.9	2247.5	2253.4	2248.9	2249.6	2249.1
	Torque / N·m	1.85	1.82	1.73	1.69	1.59	1.46	1.26
	Power / W	436.40	428.26	406.29	398.60	373.42	343.34	296.17
	T_{VL} / °C	66.0	67.3	70.5	72.0	76.0	81.5	91.1
	T_{bath} / °C	56.3	58.1	61.9	64.8	70.5	78.9	91.2
2500	Speed / rpm	2503.4	2502.0	2498.8	2500.3	2496.2	2496.4	2495.8
	Torque / N·m	1.82	1.78	1.70	1.72	1.60	1.47	1.30
	Power / W	477.50	466.13	445.93	450.11	418.42	385.52	339.29
	T_{VL} / °C	70.1	71.4	73.1	74.8	78.5	83.5	91.9
	T_{bath} / °C	59.3	61.1	64.1	66.8	71.5	78.5	91.2

Table B.20: Standard deviation of the first experimental results for the pinion and rolling bearings with a starting torque of 3 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.7	2.1	1.8	1.7	1.6	1.6	1.8
	Torque / N·m	0.28	0.30	0.30	0.29	0.29	0.28	0.27
	Power / W	14.64	15.47	15.40	14.90	15.18	14.45	14.22
750	Speed / rpm	1.4	2.0	1.3	1.5	1.4	1.3	1.3
	Torque / N·m	0.30	0.29	0.32	0.30	0.31	0.28	0.25
	Power / W	23.27	22.80	25.17	23.46	24.01	21.69	19.29
1000	Speed / rpm	1.3	1.2	1.1	1.2	1.4	1.0	1.6
	Torque / N·m	0.19	0.19	0.18	0.18	0.19	0.19	0.18
	Power / W	19.76	20.24	18.92	18.83	19.44	19.84	19.08
1500	Speed / rpm	1.3	1.6	1.3	1.4	1.1	1.3	1.3
	Torque / N·m	0.21	0.19	0.19	0.19	0.20	0.20	0.14
	Power / W	32.43	30.00	29.65	29.71	31.00	32.04	22.42
2000	Speed / rpm	1.5	1.3	1.6	1.4	1.3	1.4	1.4
	Torque / N·m	0.28	0.29	0.27	0.27	0.27	0.25	0.25
	Power / W	59.06	60.61	56.93	55.53	56.31	52.49	53.12
2250	Speed / rpm	1.7	1.6	1.5	1.5	1.4	1.3	1.2
	Torque / N·m	0.32	0.31	0.31	0.32	0.32	0.39	0.29
	Power / W	74.80	73.97	74.06	74.81	74.43	91.31	69.06
2500	Speed / rpm	1.6	1.8	2.0	1.2	1.8	1.6	1.7
	Torque / N·m	0.41	0.39	0.40	0.37	0.36	0.34	0.36
	Power / W	108.41	101.72	104.29	97.61	93.08	88.97	93.45

Table B.21: Second experimental results for the pinion and rolling bearings with a starting torque of 3 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	499.1	496.7	499.0	498.9	498.7	499.5	503.0
	Torque / N·m	1.26	1.18	1.05	0.92	0.82	0.68	0.55
	Power / W	65.93	61.37	54.86	48.17	42.61	35.65	28.86
	T_{VL} / °C	50.9	54.1	57.9	63.0	68.6	77.4	89.7
	T_{bath} / °C	50.5	53.8	57.3	62.5	68.9	78.2	91.5
750	Speed / rpm	751.0	746.9	747.0	749.4	748.8	749.4	748.4
	Torque / N·m	1.55	1.44	1.33	1.19	1.07	0.89	0.70
	Power / W	121.99	112.82	103.72	93.11	83.69	69.68	55.00
	T_{VL} / °C	52.4	55.0	58.5	62.8	68.2	77.2	90.0
	T_{bath} / °C	50.5	53.7	57.8	62.9	69.4	78.2	91.3
1000	Speed / rpm	1002.3	1001.0	997.7	1002.6	1002.5	997.6	998.0
	Torque / N·m	1.72	1.61	1.49	1.37	1.25	1.04	0.86
	Power / W	180.39	168.58	156.19	143.40	131.50	109.04	89.56
	T_{VL} / °C	53.3	56.1	59.4	63.4	68.9	76.9	88.7
	T_{bath} / °C	51.2	54.4	57.9	62.9	69.3	78.0	91.5
1500	Speed / rpm	1498.3	1500.2	1495.7	1497.1	1500.4	1498.0	1496.2
	Torque / N·m	1.84	1.70	1.69	1.57	1.47	1.30	1.08
	Power / W	289.44	267.39	264.15	246.93	230.20	204.65	168.49
	T_{VL} / °C	57.9	60.2	63.1	65.8	69.8	77.6	90.1
	T_{bath} / °C	51.5	54.7	58.3	63.2	70.0	78.1	91.3
2000	Speed / rpm	2003.4	1998.5	1999.6	2002.6	1999.2	1998.0	1998.7
	Torque / N·m	1.90	1.85	1.78	1.67	1.55	1.41	1.19
	Power / W	399.33	387.33	373.38	350.93	325.31	295.15	249.20
	T_{VL} / °C	61.9	63.9	66.8	69.1	73.5	79.3	90.6
	T_{bath} / °C	53.6	56.3	59.7	63.8	69.9	78.2	91.2
2250	Speed / rpm	2253.3	2251.9	2250.6	2249.4	2246.3	2245.2	2248.5
	Torque / N·m	1.81	1.78	1.72	1.67	1.56	1.42	1.23
	Power / W	427.08	420.82	406.35	393.31	367.33	334.70	290.45
	T_{VL} / °C	66.6	67.8	69.9	72.2	76.2	81.5	91.3
	T_{bath} / °C	56.8	58.6	61.4	65.1	70.5	78.2	91.1
2500	Speed / rpm	2500.0	2498.7	2497.3	2499.7	2498.8	2502.0	2497.0
	Torque / N·m	1.80	1.74	1.70	1.69	1.56	1.44	1.28
	Power / W	470.78	455.22	445.34	443.55	407.15	377.69	335.50
	T_{VL} / °C	70.5	71.6	73.5	75.3	78.9	83.7	92.2
	T_{bath} / °C	59.8	61.4	64.1	67.1	71.7	78.6	91.2

Table B.22: Standard deviation of the second experimental results for the pinion and rolling bearings with a starting torque of 3 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.4	1.8	1.5	1.6	1.4	1.6	1.4
	Torque / N·m	0.26	0.30	0.30	0.29	0.29	0.28	0.28
	Power / W	13.78	15.52	15.52	15.23	15.31	14.77	14.70
750	Speed / rpm	1.3	1.5	1.5	1.2	1.3	1.2	2.0
	Torque / N·m	0.32	0.33	0.33	0.31	0.30	0.27	0.27
	Power / W	25.03	25.97	26.02	24.60	23.24	21.20	21.50
1000	Speed / rpm	1.2	1.4	1.4	1.3	1.4	2.2	1.5
	Torque / N·m	0.18	0.19	0.19	0.18	0.19	0.18	0.19
	Power / W	19.03	20.27	20.14	18.87	19.81	18.54	19.75
1500	Speed / rpm	1.2	1.1	1.7	2.0	1.2	2.1	1.7
	Torque / N·m	0.18	0.18	0.20	0.20	0.20	0.20	0.18
	Power / W	28.61	28.15	30.68	30.71	31.89	31.93	27.83
2000	Speed / rpm	2.6	1.4	2.0	1.4	1.2	1.5	1.4
	Torque / N·m	0.28	0.31	0.31	0.29	0.28	0.27	0.25
	Power / W	58.92	64.17	65.89	59.91	59.14	55.91	51.56
2250	Speed / rpm	1.6	1.5	1.3	1.5	1.6	1.7	1.2
	Torque / N·m	0.31	0.36	0.36	0.37	0.34	0.31	0.29
	Power / W	74.25	83.98	85.32	86.69	80.07	73.74	69.17
2500	Speed / rpm	1.7	1.5	1.5	1.5	1.6	1.5	2.5
	Torque / N·m	0.42	0.41	0.35	0.34	0.36	0.33	0.32
	Power / W	110.50	106.64	92.76	88.83	94.46	85.16	83.58

Table B.23: Third experimental results for the pinion and rolling bearings with a starting torque of 3 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	499.7	499.0	498.9	499.4	498.6	499.6	499.9
	Torque / N·m	1.28	1.18	1.09	0.93	0.82	0.69	0.53
	Power / W	67.01	61.70	57.10	48.79	42.84	36.08	27.99
	T_{VL} / °C	50.8	54.0	57.9	62.8	68.5	77.3	89.8
	T_{bath} / °C	50.2	53.4	57.2	62.5	69.0	78.4	91.5
750	Speed / rpm	750.2	750.1	749.3	746.4	752.3	746.4	748.9
	Torque / N·m	1.57	1.38	1.39	1.19	1.08	0.90	0.73
	Power / W	123.37	108.19	108.93	92.73	85.42	70.53	57.29
	T_{VL} / °C	51.9	54.7	58.1	62.7	68.2	77.3	89.6
	T_{bath} / °C	50.2	53.4	58.1	63.0	69.4	78.2	91.2
1000	Speed / rpm	1002.9	1001.4	998.0	997.2	999.6	999.5	998.5
	Torque / N·m	1.73	1.64	1.53	1.39	1.28	1.07	0.87
	Power / W	181.94	171.93	159.94	145.12	134.30	111.98	91.27
	T_{VL} / °C	53.1	55.6	58.9	63.1	68.9	77.0	88.1
	T_{bath} / °C	51.0	54.3	57.8	62.9	69.4	78.3	91.2
1500	Speed / rpm	1504.9	1498.1	1500.0	1498.5	1496.7	1503.3	1499.5
	Torque / N·m	1.89	1.81	1.82	1.59	1.46	1.31	1.02
	Power / W	298.53	284.49	285.56	249.59	228.09	206.94	160.53
	T_{VL} / °C	57.1	59.7	62.3	66.2	69.9	77.5	89.7
	T_{bath} / °C	51.4	54.7	58.5	63.2	69.6	78.1	91.1
2000	Speed / rpm	2001.6	1999.6	2001.2	2000.1	1995.7	1999.0	1999.3
	Torque / N·m	1.87	1.84	1.76	1.63	1.57	1.40	1.22
	Power / W	392.41	385.67	369.00	341.85	328.00	293.42	254.81
	T_{VL} / °C	62.0	63.8	66.5	69.5	72.8	79.0	90.4
	T_{bath} / °C	53.6	56.1	59.6	63.8	69.6	78.2	91.2
2250	Speed / rpm	2255.0	2252.7	2251.3	2250.4	2249.6	2249.7	2249.3
	Torque / N·m	1.83	1.78	1.72	1.65	1.57	1.45	1.25
	Power / W	432.62	420.83	406.50	389.31	370.67	342.69	294.95
	T_{VL} / °C	66.2	67.6	70.0	72.5	75.4	83.1	91.1
	T_{bath} / °C	56.3	58.3	61.4	65.3	70.2	78.2	91.2
2500	Speed / rpm	2503.8	2499.5	2498.1	2500.2	2496.2	2497.0	2496.1
	Torque / N·m	1.80	1.83	1.71	1.70	1.58	1.45	1.28
	Power / W	471.25	478.45	448.51	445.55	412.85	377.93	334.15
	T_{VL} / °C	70.0	71.4	73.3	75.2	78.2	83.5	91.9
	T_{bath} / °C	59.3	61.0	63.7	67.0	71.4	78.5	91.1

Table B.24: Standard deviation of the third experimental results for the pinion and rolling bearings with a starting torque of 3 N·m.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.1	1.8	1.5	1.4	1.8	1.6	1.1
	Torque / N·m	0.28	0.29	0.29	0.29	0.29	0.28	0.29
	Power / W	14.65	14.92	15.26	14.96	15.24	14.56	15.01
750	Speed / rpm	1.9	1.3	1.4	1.6	1.3	1.6	1.6
	Torque / N·m	0.32	0.32	0.31	0.31	0.32	0.27	0.27
	Power / W	25.10	25.05	24.60	23.88	24.98	21.00	21.30
1000	Speed / rpm	1.4	1.4	1.3	1.4	1.2	1.1	1.3
	Torque / N·m	0.19	0.19	0.19	0.20	0.21	0.17	0.18
	Power / W	19.59	20.18	19.75	21.08	22.42	17.64	19.27
1500	Speed / rpm	1.8	1.2	1.2	1.3	2.4	2.0	1.3
	Torque / N·m	0.19	0.20	0.20	0.20	0.19	0.19	0.15
	Power / W	30.34	30.78	31.09	31.13	29.24	29.57	23.69
2000	Speed / rpm	1.4	1.2	1.4	1.7	2.3	1.3	1.5
	Torque / N·m	0.26	0.26	0.28	0.32	0.28	0.27	0.25
	Power / W	54.07	54.46	59.53	66.60	57.94	56.26	52.45
2250	Speed / rpm	1.6	1.4	1.4	1.4	1.4	1.3	1.1
	Torque / N·m	0.33	0.35	0.34	0.27	0.34	0.37	0.30
	Power / W	77.44	81.72	79.24	63.48	79.89	87.77	70.35
2500	Speed / rpm	1.7	1.5	1.3	1.4	1.8	1.6	1.6
	Torque / N·m	0.40	0.41	0.39	0.39	0.36	0.37	0.35
	Power / W	105.39	107.43	102.94	102.01	94.97	97.40	92.07

B.3 Pinion Rolling Bearings Power Loss results for different Oil Flow Rates

Table B.25: Pinion rolling bearings results for different oil flow rates - 50 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$					
		0.15	0.19	0.22	0.29	0.40	0.53
500	Speed / rpm	498.9	498.9	499.0	498.8	499.6	499.1
	Torque / N·m	0.82	0.83	0.85	1.01	0.98	1.08
	Power / W	42.69	43.59	44.36	52.58	51.10	56.53
	T_{VL} / °C	50.0	50.4	49.8	50.2	50.0	50.0
750	Speed / rpm	749.4	747.1	452.8	746.9	749.8	750.9
	Torque / N·m	1.09	1.12	1.12	1.29	1.36	1.32
	Power / W	85.90	87.33	87.99	100.54	107.11	104.14
	T_{VL} / °C	50.8	50.9	48.9	48.7	48.8	49.2
1000	Speed / rpm	999.8	999.9	1000.0	1000.7	1000.6	1002.2
	Torque / N·m	1.23	1.25	1.29	1.42	1.43	1.51
	Power / W	128.76	130.68	134.65	149.08	149.71	158.15
	T_{VL} / °C	50.8	50.9	49.4	49.5	49.4	49.5
1500	Speed / rpm	1495.0	1496.1	1497.8	1498.7	1500.6	1498.5
	Torque / N·m	1.39	1.38	1.39	1.47	1.65	1.72
	Power / W	217.66	216.03	217.60	230.10	258.86	270.31
	T_{VL} / °C	52.5	52.1	50.8	50.2	49.9	49.8
2000	Speed / rpm	2000.6	2000.1	2000.5	1998.0	1999.0	2000.1
	Torque / N·m	1.53	1.52	1.58	1.56	1.79	1.80
	Power / W	321.27	317.40	330.59	325.67	374.14	376.75
	T_{VL} / °C	51.8	51.9	50.7	51.0	51.2	51.1
2250	Speed / rpm	2251.0	2250.3	2251.6	2250.7	2249.0	2254.2
	Torque / N·m	1.48	1.50	1.50	1.46	1.69	1.76
	Power / W	348.93	353.60	354.54	343.72	396.99	414.52
	T_{VL} / °C	55.7	53.0	51.4	50.4	51.3	51.9
2500	Speed / rpm	2500.1	2500.5	2501.8	2501.2	2499.7	2503.2
	Torque / N·m	1.40	1.46	1.45	1.44	1.72	1.77
	Power / W	365.27	382.22	379.98	377.81	449.61	463.34
	T_{VL} / °C	58.8	55.5	52.6	50.6	51.6	52.2

Table B.26: Standard deviation of the pinion rolling bearings results for different oil flow rates - 50 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$					
		0.15	0.19	0.22	0.29	0.40	0.53
500	Speed / rpm	1.6	1.7	1.7	1.6	1.6	1.6
	Torque / N·m	0.26	0.26	0.26	0.25	0.26	0.21
	Power / W	13.36	13.47	13.67	13.10	13.60	10.97
750	Speed / rpm	1.5	2.0	3.1	1.4	1.1	1.4
	Torque / N·m	0.27	0.27	0.27	0.27	0.24	0.23
	Power / W	21.06	20.83	21.02	21.03	19.17	18.07
1000	Speed / rpm	1.2	1.1	1.1	1.1	1.0	1.4
	Torque / N·m	0.17	0.19	0.18	0.17	0.18	0.14
	Power / W	18.23	20.14	18.68	17.40	18.46	15.20
1500	Speed / rpm	1.9	2.4	1.5	1.2	1.3	1.3
	Torque / N·m	0.21	0.19	0.19	0.21	0.17	0.21
	Power / W	32.70	30.28	30.50	32.32	26.36	33.15
2000	Speed / rpm	1.8	1.3	2.2	1.4	1.6	2.0
	Torque / N·m	0.32	0.22	0.25	0.30	0.27	0.31
	Power / W	66.29	45.29	52.62	63.56	56.37	65.17
2250	Speed / rpm	2.1	1.5	2.0	1.2	1.4	1.6
	Torque / N·m	0.32	0.39	0.32	0.32	0.34	0.32
	Power / W	76.56	91.36	75.85	76.37	80.90	74.79
2500	Speed / rpm	1.6	1.6	2.2	1.5	1.3	1.5
	Torque / N·m	0.44	0.43	0.43	0.44	0.46	0.46
	Power / W	114.71	113.87	112.33	114.04	120.39	119.37

Table B.27: Pinion rolling bearings results for different oil flow rates - 53.3 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$						
		0.15	0.18	0.21	0.23	0.30	0.43	0.56
500	Speed / rpm	499.3	499.4	499.5	499.3	499.9	497.1	500.8
	Torque / N·m	0.84	0.93	0.92	0.90	0.99	1.01	1.05
	Power / W	43.84	48.78	48.05	47.24	51.96	52.35	54.88
	T_{VL} / °C	52.7	53.4	53.0	53.6	53.3	53.1	53.1
750	Speed / rpm	752.1	748.5	750.2	750.2	750.7	747.9	751.5
	Torque / N·m	1.13	1.12	1.18	1.23	1.24	1.28	1.30
	Power / W	89.00	87.71	92.84	96.96	97.61	100.18	102.26
	T_{VL} / °C	53.8	53.7	51.4	53.2	53.0	51.9	52.9
1000	Speed / rpm	1000.7	999.9	1000.7	1000.6	1001.4	1002.0	1002.5
	Torque / N·m	1.26	1.21	1.31	1.29	1.41	1.44	1.47
	Power / W	131.88	126.25	137.66	135.22	147.87	150.93	153.96
	T_{VL} / °C	54.4	54.2	51.6	54.0	53.5	52.3	53.0
1500	Speed / rpm	1498.0	1494.9	1498.5	1497.5	1499.7	1496.9	1499.4
	Torque / N·m	1.39	1.42	1.43	1.42	1.58	1.63	1.67
	Power / W	218.19	222.24	224.33	223.13	248.67	255.53	261.69
	T_{VL} / °C	55.2	55.6	53.1	55.0	54.4	53.3	53.1
2000	Speed / rpm	2000.3	1999.5	2000.5	1997.8	1999.8	2000.6	2000.2
	Torque / N·m	1.46	1.44	1.46	1.49	1.64	1.70	1.72
	Power / W	305.73	302.22	305.86	311.51	343.74	356.25	359.31
	T_{VL} / °C	56.9	55.8	53.2	55.3	55.4	54.3	54.3
2250	Speed / rpm	2251.8	2250.1	2252.0	2249.7	2249.9	2256.9	2252.5
	Torque / N·m	1.52	1.54	1.59	1.57	1.48	1.64	1.75
	Power / W	357.86	362.88	374.58	369.07	348.15	387.18	411.94
	T_{VL} / °C	61.3	58.0	53.8	55.8	56.2	55.4	55.1
2500	Speed / rpm	2498.7	2502.5	2499.0	2499.6	2498.4	2500.6	2496.9
	Torque / N·m	1.56	1.50	1.57	1.46	1.46	1.65	1.74
	Power / W	408.84	392.68	410.13	381.29	381.14	432.41	455.03
	T_{VL} / °C	61.4	60.8	56.1	56.9	56.1	55.7	55.0

Table B.28: Standard deviation of the pinion rolling bearings results for different oil flow rates - 53.3 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$						
		0.15	0.18	0.21	0.23	0.30	0.43	0.56
500	Speed / rpm	1.5	1.4	1.6	2.1	1.4	1.5	1.5
	Torque / N·m	0.25	0.23	0.23	0.24	0.23	0.21	0.17
	Power / W	13.00	11.95	12.15	12.54	11.86	11.15	8.87
750	Speed / rpm	1.6	2.1	1.4	1.2	1.6	1.4	1.3
	Torque / N·m	0.25	0.21	0.23	0.23	0.23	0.22	0.18
	Power / W	19.90	16.68	18.44	17.93	18.04	17.34	14.42
1000	Speed / rpm	1.4	1.4	1.4	1.4	1.3	1.4	1.4
	Torque / N·m	0.16	0.21	0.16	0.17	0.16	0.16	0.14
	Power / W	17.07	21.53	16.30	17.85	16.74	17.24	14.97
1500	Speed / rpm	1.5	1.7	1.4	1.3	1.0	1.6	1.3
	Torque / N·m	0.21	0.20	0.19	0.21	0.25	0.19	0.19
	Power / W	32.67	31.93	29.77	32.31	39.21	30.18	29.49
2000	Speed / rpm	1.3	2.3	1.2	1.5	1.2	1.4	1.6
	Torque / N·m	0.30	0.34	0.38	0.27	0.31	0.16	0.34
	Power / W	63.71	70.28	79.61	55.74	65.56	54.31	70.88
2250	Speed / rpm	1.8	2.2	1.8	1.7	1.4	2.3	2.4
	Torque / N·m	0.34	0.31	0.34	0.33	0.21	0.22	0.29
	Power / W	80.66	73.08	79.57	76.81	49.82	80.46	69.46
2500	Speed / rpm	1.5	1.7	1.8	1.8	1.4	1.2	1.5
	Torque / N·m	0.46	0.47	0.47	0.43	0.47	0.21	0.47
	Power / W	120.76	122.65	121.95	113.73	123.94	124.72	123.05

Table B.29: Pinion rolling bearings results for different oil flow rates - 57.3 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$					
		0.15	0.17	0.23	0.29	0.31	0.37
500	Speed / rpm	499.6	499.9	497.2	499.4	499.5	499.5
	Torque / N·m	0.79	0.83	0.84	0.82	0.76	0.76
	Power / W	41.08	43.32	43.91	42.86	39.87	39.94
	T_{VL} / °C	57.7	57.9	56.9	57.1	57.4	57.9
750	Speed / rpm	749.4	747.8	751.2	749.6	749.5	749.5
	Torque / N·m	1.04	1.09	1.12	1.07	1.01	1.03
	Power / W	81.70	85.17	87.83	83.80	79.44	80.94
	T_{VL} / °C	57.2	57.2	56.0	57.4	56.9	56.1
1000	Speed / rpm	999.1	1000.4	1005.1	997.5	999.6	999.6
	Torque / N·m	1.16	1.20	1.23	1.22	1.15	1.21
	Power / W	121.77	125.42	129.17	127.86	120.64	126.57
	T_{VL} / °C	58.3	58.3	57.1	58.0	57.3	56.1
1500	Speed / rpm	1498.3	1498.4	1502.7	1497.6	1498.0	1501.7
	Torque / N·m	1.27	1.29	1.32	1.33	1.37	1.42
	Power / W	198.49	201.78	207.82	208.58	215.23	223.35
	T_{VL} / °C	59.8	59.6	57.5	58.8	58.1	57.0
2000	Speed / rpm	1999.0	1999.9	2004.2	2001.3	1995.5	2000.9
	Torque / N·m	1.37	1.14	1.42	1.39	1.41	1.51
	Power / W	287.40	237.99	298.13	292.00	295.08	316.07
	T_{VL} / °C	61.9	60.9	57.8	59.0	59.1	58.4
2250	Speed / rpm	2253.4	2253.7	2255.7	2254.2	2251.5	2248.4
	Torque / N·m	1.53	1.48	1.57	1.34	1.36	1.47
	Power / W	360.57	348.48	370.24	316.59	321.00	345.30
	T_{VL} / °C	65.4	63.5	58.6	58.6	60.0	59.6
2500	Speed / rpm	2503.0	2503.8	2501.6	2502.9	2495.7	2499.2
	Torque / N·m	1.52	1.50	1.56	1.66	1.41	1.52
	Power / W	399.56	392.42	409.22	435.84	368.02	396.69
	T_{VL} / °C	69.1	66.3	60.5	59.1	58.2	59.8

Table B.30: Standard deviation of the pinion rolling bearings results for different oil flow rates - 57.3 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$					
		0.15	0.17	0.23	0.29	0.31	0.37
500	Speed / rpm	1.3	1.4	1.6	1.5	1.7	1.3
	Torque / N·m	0.22	0.22	0.20	0.23	0.22	0.23
	Power / W	11.67	11.32	10.22	12.12	11.68	12.5
750	Speed / rpm	1.6	1.3	1.3	1.2	1.2	1.2
	Torque / N·m	0.22	0.20	0.20	0.24	0.23	0.24
	Power / W	17.58	15.66	15.35	18.55	18.39	19.10
1000	Speed / rpm	1.6	1.1	1.7	1.1	1.2	1.1
	Torque / N·m	0.18	0.17	0.15	0.19	0.19	0.18
	Power / W	18.51	17.85	16.14	20.06	19.49	19.19
1500	Speed / rpm	1.2	1.1	1.5	1.5	1.4	1.2
	Torque / N·m	0.20	0.19	0.20	0.21	0.20	0.20
	Power / W	31.02	29.70	31.69	33.31	31.23	31.77
2000	Speed / rpm	1.7	1.4	1.7	1.4	1.7	1.3
	Torque / N·m	0.24	0.16	0.26	0.34	0.29	0.27
	Power / W	50.73	34.43	54.51	70.27	61.54	57.56
2250	Speed / rpm	1.6	1.7	1.7	1.4	1.4	1.5
	Torque / N·m	0.33	0.33	0.33	0.32	0.32	0.32
	Power / W	78.24	77.87	78.60	75.87	75.20	75.49
2500	Speed / rpm	1.9	1.8	2.2	1.5	1.8	1.4
	Torque / N·m	0.50	0.49	0.50	0.48	0.46	0.45
	Power / W	130.80	128.39	130.38	126.23	121.40	118.89

Table B.31: Pinion rolling bearings results for different oil flow rates - 62.2 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$					
		0.17	0.19	0.26	0.33	0.45	0.63
500	Speed / rpm	499.5	499.4	499.7	497.1	500.1	497.8
	Torque / N·m	0.84	0.76	0.79	0.76	0.78	0.82
	Power / W	44.19	39.57	41.20	39.74	40.65	42.52
	T_{VL} / °C	62.1	62.0	62.2	62.1	62.3	62.3
750	Speed / rpm	747.4	750.0	749.8	750.2	747.9	748.5
	Torque / N·m	1.07	0.98	1.03	0.99	1.03	1.06
	Power / W	83.87	77.22	80.69	78.05	81.01	83.44
	T_{VL} / °C	59.3	60.2	62.1	61.9	61.5	62.4
1000	Speed / rpm	997.9	1000.0	1000.2	998.2	1001.1	1001.9
	Torque / N·m	1.20	1.15	1.16	1.17	1.20	1.23
	Power / W	125.19	120.95	121.82	122.75	125.58	128.66
	T_{VL} / °C	60.4	61.0	62.5	62.1	61.6	62.2
1500	Speed / rpm	1497.5	1497.8	1498.2	1498.3	1498.9	1500.3
	Torque / N·m	1.32	1.24	1.28	1.32	1.37	1.39
	Power / W	207.11	195.10	200.61	206.95	214.42	218.89
	T_{VL} / °C	62.0	62.5	62.7	63.2	62.4	62.5
2000	Speed / rpm	1997.9	1996.8	1998.7	1998.9	2000.7	1999.5
	Torque / N·m	1.41	1.37	1.34	1.31	1.53	1.59
	Power / W	295.51	286.45	280.80	274.26	320.14	332.80
	T_{VL} / °C	62.9	63.4	62.3	63.7	63.4	63.2
2250	Speed / rpm	2251.9	2251.9	2252.4	2252.7	2253.4	2249.5
	Torque / N·m	1.43	1.38	1.39	1.32	1.48	1.53
	Power / W	337.22	324.30	329.00	310.61	349.78	360.28
	T_{VL} / °C	65.1	64.8	62.8	64.4	64.3	63.6
2500	Speed / rpm	2499.9	2502.0	2499.2	2502.2	2500.0	2502.5
	Torque / N·m	1.56	1.51	1.37	1.37	1.44	1.46
	Power / W	382.88	376.74	357.45	358.73	394.25	407.85
	T_{VL} / °C	68.3	66.8	63.8	64.6	64.6	63.8

Table B.32: Standard deviation of the pinion rolling bearings results for different oil flow rates - 62.2 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$					
		0.17	0.19	0.26	0.33	0.45	0.63
500	Speed / rpm	1.5	1.5	1.5	1.7	1.5	1.6
	Torque / N·m	0.21	0.24	0.24	0.22	0.22	0.20
	Power / W	11.13	12.73	12.32	11.66	11.60	10.55
750	Speed / rpm	1.3	1.4	1.4	1.2	1.3	1.2
	Torque / N·m	0.20	0.21	0.24	0.21	0.23	0.22
	Power / W	15.89	16.34	19.07	16.76	17.76	17.14
1000	Speed / rpm	1.6	1.1	1.1	1.3	1.5	1.5
	Torque / N·m	0.15	0.14	0.18	0.17	0.18	0.18
	Power / W	15.86	15.05	18.64	18.17	18.81	19.10
1500	Speed / rpm	1.3	1.3	1.2	1.2	1.7	1.3
	Torque / N·m	0.21	0.21	0.20	0.21	0.19	0.19
	Power / W	33.16	33.01	31.60	32.86	29.58	29.09
2000	Speed / rpm	1.4	2.1	1.2	1.9	1.5	1.5
	Torque / N·m	0.31	0.31	0.34	0.27	0.27	0.21
	Power / W	65.07	64.78	72.03	56.66	55.99	44.99
2250	Speed / rpm	1.6	1.5	1.5	1.3	1.6	1.2
	Torque / N·m	0.34	0.32	0.32	0.32	0.33	0.32
	Power / W	79.55	75.43	76.14	74.58	76.68	76.53
2500	Speed / rpm	2.2	1.8	1.7	1.7	1.7	1.3
	Torque / N·m	0.46	0.46	0.44	0.45	0.47	0.47
	Power / W	120.68	119.29	114.52	117.85	123.92	123.78

Table B.33: Pinion rolling bearings results for different oil flow rates - 68.5 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$				
		0.16	0.22	0.30	0.40	0.51
500	Speed / rpm	502.0	499.8	499.9	500.0	500.6
	Torque / N·m	0.68	0.63	0.68	0.65	0.73
	Power / W	35.56	33.09	35.41	34.16	38.04
	T_{VL} / °C	68.1	68.1	68.7	68.4	68.4
750	Speed / rpm	750.2	750.3	750.5	750.6	750.9
	Torque / N·m	0.93	0.89	0.91	0.88	0.95
	Power / W	72.74	69.72	71.38	69.05	74.98
	T_{VL} / °C	67.6	67.8	68.5	67.6	68.4
1000	Speed / rpm	997.0	999.7	1000.7	1000.8	1004.0
	Torque / N·m	1.01	1.00	1.05	1.04	1.09
	Power / W	105.51	105.21	109.79	109.08	114.71
	T_{VL} / °C	67.7	65.7	68.7	67.6	68.1
1500	Speed / rpm	1500.2	1497.9	1500.7	1498.5	1503.1
	Torque / N·m	1.10	1.17	1.14	1.26	1.29
	Power / W	173.23	183.00	179.64	197.57	202.90
	T_{VL} / °C	68.1	67.3	68.9	67.8	68.5
2000	Speed / rpm	1998.3	1998.9	1998.9	1999.7	2000.7
	Torque / N·m	1.38	1.27	1.29	1.40	1.39
	Power / W	288.58	266.62	269.55	292.40	291.00
	T_{VL} / °C	69.7	.8.6	69.0	69.1	69.6
2250	Speed / rpm	2251.8	2254.7	2252.2	2252.5	2252.8
	Torque / N·m	1.28	1.30	1.33	1.36	1.38
	Power / W	302.40	306.33	312.94	320.46	325.23
	T_{VL} / °C	73.1	70.0	69.4	69.8	70.5
2500	Speed / rpm	2501.2	2501.7	2499.1	2499.8	2504.2
	Torque / N·m	1.27	1.31	1.31	1.46	1.41
	Power / W	332.94	343.07	341.95	381.81	369.29
	T_{VL} / °C	71.2	70.2	70.0	71.4	75.0

Table B.34: Standard deviation of the pinion rolling bearings results for different oil flow rates - 68.5 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$				
		0.16	0.22	0.30	0.40	0.51
500	Speed / rpm	2.3	1.5	1.6	1.5	1.6
	Torque / N·m	0.25	0.23	0.22	0.24	0.20
	Power / W	12.95	12.26	11.63	12.47	10.66
750	Speed / rpm	1.1	1.2	1.4	1.2	1.3
	Torque / N·m	0.22	0.23	0.23	0.23	0.20
	Power / W	17.66	18.17	17.83	17.97	15.83
1000	Speed / rpm	1.6	1.4	1.3	1.1	1.6
	Torque / N·m	0.16	0.16	0.17	0.18	0.17
	Power / W	16.62	17.00	17.44	18.41	17.47
1500	Speed / rpm	0.9	1.5	1.2	1.3	1.4
	Torque / N·m	0.15	0.20	0.20	0.22	0.21
	Power / W	24.07	32.08	31.64	33.81	33.28
2000	Speed / rpm	1.7	1.4	1.3	1.4	1.8
	Torque / N·m	0.32	0.29	0.34	0.25	0.29
	Power / W	67.41	60.45	71.85	52.04	59.96
2250	Speed / rpm	1.7	1.8	1.5	1.4	2.0
	Torque / N·m	0.30	0.33	0.32	0.32	0.33
	Power / W	71.67	77.97	76.49	76.19	77.71
2500	Speed / rpm	1.6	1.8	1.4	1.8	1.9
	Torque / N·m	0.43	0.44	0.45	0.48	0.48
	Power / W	111.90	116.05	117.94	126.12	125.00

Table B.35: Pinion rolling bearings results for different oil flow rates - 77.1 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$					
		0.17	0.22	0.29	0.37	0.47	0.62
500	Speed / rpm	500.5	499.3	500.6	500.7	499.9	500.6
	Torque / N·m	0.58	0.57	0.55	0.53	0.55	0.53
	Power / W	30.26	29.55	28.57	27.61	28.79	27.60
	T_{VL} / °C	77.1	77.0	77.2	77.0	77.0	76.8
750	Speed / rpm	749.7	743.3	750.3	746.8	750.5	750.7
	Torque / N·m	0.77	0.75	0.73	0.73	0.74	0.77
	Power / W	60.56	58.77	57.55	57.06	58.14	60.75
	T_{VL} / °C	76.1	74.6	76.8	76.4	76.1	76.9
1000	Speed / rpm	996.9	996.9	999.9	999.6	999.8	1001.2
	Torque / N·m	0.88	0.90	0.88	0.88	0.87	0.90
	Power / W	92.15	94.45	92.51	92.12	91.44	94.52
	T_{VL} / °C	74.8	73.5	77.5	76.0	76.0	76.9
1500	Speed / rpm	1500.6	1500.5	1497.1	1495.0	1501.6	1502.1
	Torque / N·m	1.05	1.03	1.02	1.07	1.09	1.11
	Power / W	164.35	162.46	159.53	166.78	171.06	174.44
	T_{VL} / °C	74.4	73.8	77.6	77.3	76.4	77.6
2000	Speed / rpm	2001.5	2002.1	2002.4	1999.5	2001.2	2004.6
	Torque / N·m	1.13	1.16	1.12	1.13	1.22	1.24
	Power / W	236.16	243.52	233.95	237.54	254.96	260.22
	T_{VL} / °C	76.8	75.6	77.4	77.8	77.4	77.6
2250	Speed / rpm	2251.9	2252.2	2255.8	2252.7	2254.5	2254.9
	Torque / N·m	1.19	1.22	1.14	1.11	1.21	1.26
	Power / W	279.93	287.91	269.24	262.35	285.37	298.25
	T_{VL} / °C	79.1	76.9	78.1	78.1	77.9	78.0
2500	Speed / rpm	2498.3	2502.3	2502.8	2499.8	2502.6	2504.2
	Torque / N·m	1.15	1.22	1.35	1.15	1.18	1.30
	Power / W	300.46	318.64	354.58	299.82	309.43	342.19
	T_{VL} / °C	81.6	78.5	79.1	78.3	78.2	78.5

Table B.36: Standard deviation of the pinion rolling bearings results for different oil flow rates - 77.1 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$					
		0.17	0.22	0.29	0.37	0.47	0.62
500	Speed / rpm	1.5	1.9	1.5	1.6	1.9	1.7
	Torque / N·m	0.21	0.22	0.23	0.21	0.20	0.18
	Power / W	10.87	11.40	12.07	11.25	10.42	9.36
750	Speed / rpm	1.5	1.6	1.3	1.5	1.3	1.3
	Torque / N·m	0.21	0.21	0.23	0.20	0.20	0.20
	Power / W	16.46	16.29	17.98	15.29	15.56	15.36
1000	Speed / rpm	1.4	1.5	1.4	1.3	1.4	1.3
	Torque / N·m	0.16	0.18	0.17	0.18	0.19	0.17
	Power / W	17.00	19.22	18.01	18.39	19.73	17.69
1500	Speed / rpm	1.4	1.3	1.4	1.7	1.4	1.3
	Torque / N·m	0.20	0.21	0.21	0.20	0.21	0.21
	Power / W	31.13	33.03	32.18	31.24	32.93	33.24
2000	Speed / rpm	1.4	1.5	1.5	1.2	1.3	1.8
	Torque / N·m	0.29	0.27	0.24	0.24	0.25	0.23
	Power / W	59.82	57.64	50.11	49.28	51.39	49.12
2250	Speed / rpm	1.5	1.4	1.6	1.5	1.6	1.7
	Torque / N·m	0.34	0.33	0.33	0.31	0.32	0.33
	Power / W	80.35	77.73	78.23	72.22	76.39	78.24
2500	Speed / rpm	1.4	1.5	1.6	1.4	2.0	2.0
	Torque / N·m	0.46	0.48	0.49	0.41	0.44	0.48
	Power / W	119.59	125.98	127.20	108.53	114.69	125.89

Table B.37: Pinion rolling bearings results for different oil flow rates - 90 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$				
		0.20	0.24	0.27	0.38	0.50
500	Speed / rpm	501.0	500.6	501.2	501.5	500.8
	Torque / N·m	0.45	0.47	0.44	0.41	0.41
	Power / W	23.77	24.80	23.10	21.1	21.57
	T_{VL} / °C	90.2	89.8	90.4	90.3	90.3
750	Speed / rpm	749.4	749.5	749.7	749.7	747.4
	Torque / N·m	0.62	0.64	0.62	0.59	0.56
	Power / W	48.67	50.16	48.90	46.26	43.82
	T_{VL} / °C	85.3	90.4	88.7	88.3	90.6
1000	Speed / rpm	999.5	999.3	1002.3	997.1	1000.0
	Torque / N·m	0.74	0.76	0.72	0.71	0.65
	Power / W	77.19	79.61	75.29	74.24	68.02
	T_{VL} / °C	83.4	90.4	90.2	88.4	90.9
1500	Speed / rpm	1496.8	1496.8	1497.1	1497.5	1497.6
	Torque / N·m	0.88	0.92	0.86	0.85	0.87
	Power / W	137.50	144.71	134.77	133.66	137.15
	T_{VL} / °C	92.7	89.7	86.2	88.4	91.0
2000	Speed / rpm	1999.1	2001.9	1999.4	2000.5	2000.4
	Torque / N·m	1.15	1.09	0.99	0.96	0.99
	Power / W	240.27	228.02	207.02	200.77	207.02
	T_{VL} / °C	94.4	89.5	86.3	88.1	90.9
2250	Speed / rpm	2249.3	2251.6	2249.2	2252.9	2251.4
	Torque / N·m	1.03	1.03	0.99	0.97	1.03
	Power / W	243.17	242.54	233.72	228.32	241.96
	T_{VL} / °C	94.8	89.6	86.8	88.2	91.5
2500	Speed / rpm	2498.8	2501.4	2499.6	2499.8	2504.0
	Torque / N·m	1.00	1.10	1.01	1.10	1.05
	Power / W	260.73	288.75	265.26	287.68	276.34
	T_{VL} / °C	94.7	90.1	87.6	88.7	91.9

Table B.38: Standard deviation of the pinion rolling bearings results for different oil flow rates - 90 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$				
		0.20	0.24	0.27	0.38	0.50
500	Speed / rpm	1.5	1.4	1.4	1.4	1.4
	Torque / N·m	0.21	0.20	0.22	0.21	0.19
	Power / W	10.88	10.35	11.61	11.11	9.71
750	Speed / rpm	1.3	1.2	1.4	1.4	1.6
	Torque / N·m	0.20	0.19	0.21	0.21	0.18
	Power / W	15.44	14.92	16.28	16.21	14.15
1000	Speed / rpm	1.2	1.4	1.3	1.5	1.0
	Torque / N·m	0.16	0.16	0.18	0.18	0.17
	Power / W	17.17	16.82	18.77	18.85	18.09
1500	Speed / rpm	1.5	1.5	1.3	1.3	1.2
	Torque / N·m	0.20	0.21	0.19	0.20	0.22
	Power / W	32.01	33.27	30.45	31.18	34.63
2000	Speed / rpm	1.6	1.4	1.3	1.2	1.3
	Torque / N·m	0.32	0.25	0.26	0.25	0.29
	Power / W	66.29	52.75	53.57	52.29	61.40
2250	Speed / rpm	1.2	1.3	1.4	1.4	1.1
	Torque / N·m	0.32	0.32	0.37	0.32	0.31
	Power / W	75.12	76.59	86.32	74.97	72.39
2500	Speed / rpm	1.2	1.6	1.5	1.4	1.7
	Torque / N·m	0.46	0.48	0.44	0.48	0.44
	Power / W	119.28	125.26	115.28	125.90	116.16

B.4 Pinion Power Loss results with Rolling Bearings in overflow

Table B.39: First experimental results for pinion power loss results with rolling bearings in overflow.

Speed rpm	Variable	Test	
		Rolling Bearing	Pinion + Rolling Bearing
500	Speed / rpm	499.84	499.51
	Torque / N·m	1.04	1.12
	Power / W	54.57	58.59
	T_{VL} / °C	50.8	50.0
	T_{bath} / °C	-	50.2
750	Speed / rpm	749.91	750.04
	Torque / N·m	1.43	1.44
	Power / W	112.51	112.79
	T_{VL} / °C	50.7	50.2
	T_{bath} / °C	-	49.7
1000	Speed / rpm	1001.01	1001.51
	Torque / N·m	1.59	1.80
	Power / W	166.79	188.28
	T_{VL} / °C	50.9	50.6
	T_{bath} / °C	-	50.9
1500	Speed / rpm	1500.32	1500.44
	Torque / N·m	1.84	1.97
	Power / W	288.66	310.29
	T_{VL} / °C	51.7	51.4
	T_{bath} / °C	-	52.1
2000	Speed / rpm	2002.78	2002.38
	Torque / N·m	2.09	2.12
	Power / W	438.43	443.95
	T_{VL} / °C	52.3	52.0
	T_{bath} / °C	-	53.4
2250	Speed / rpm	2253.83	2250.12
	Torque / N·m	2.20	2.29
	Power / W	518.34	538.65
	T_{VL} / °C	53.0	52.6
	T_{bath} / °C	-	54.8
2500	Speed / rpm	2502.64	2499.48
	Torque / N·m	2.22	2.26
	Power / W	581.26	590.49
	T_{VL} / °C	54.2	53.7
	T_{bath} / °C	-	55.7

Table B.40: Standard deviation of the first experimental results for pinion power loss results with rolling bearings in overflow.

Speed rpm	Variable	Test	
		Rolling Bearing	Pinion + Rolling Bearing
500	Speed / rpm	1.6	1.3
	Torque / N·m	0.30	0.27
	Power / W	15.47	13.97
750	Speed / rpm	1.2	1.1
	Torque / N·m	0.30	0.27
	Power / W	23.94	21.11
1000	Speed / rpm	1.1	1.5
	Torque / N·m	0.19	0.18
	Power / W	20.33	19.28
1500	Speed / rpm	0.9	1.4
	Torque / N·m	0.12	0.21
	Power / W	19.43	33.39
2000	Speed / rpm	1.8	1.4
	Torque / N·m	0.31	0.28
	Power / W	64.63	59.53
2250	Speed / rpm	1.7	1.4
	Torque / N·m	0.35	0.54
	Power / W	83.68	126.56
2500	Speed / rpm	1.5	1.3
	Torque / N·m	0.50	0.50
	Power / W	130.26	129.71

Table B.41: Second experimental results for pinion power loss results with rolling bearings in overflow.

Speed rpm	Variable	Test	
		Rolling Bearing	Pinion + Rolling Bearing
500	Speed / rpm	497.2	499.1
	Torque / N·m	1.12	1.09
	Power / W	58.16	56.89
	T_{VL} / °C	49.8	49.9
	T_{bath} / °C	-	50.1
750	Speed / rpm	751.8	747.4
	Torque / N·m	1.56	1.52
	Power / W	122.48	118.71
	T_{VL} / °C	50.2	50.0
	T_{bath} / °C	-	49.6
1000	Speed / rpm	1002.6	1001.7
	Torque / N·m	1.66	1.77
	Power / W	174.03	185.87
	T_{VL} / °C	50.5	50.5
	T_{bath} / °C	-	50.9
1500	Speed / rpm	1502.1	1501.2
	Torque / N·m	1.97	2.01
	Power / W	309.48	316.77
	T_{VL} / °C	51.4	51.2
	T_{bath} / °C	-	51.9
2000	Speed / rpm	2003.3	2000.7
	Torque / N·m	2.13	2.13
	Power / W	447.36	446.28
	T_{VL} / °C	52.0	51.8
	T_{bath} / °C	-	53.6
2250	Speed / rpm	2253.5	2252.2
	Torque / N·m	2.18	2.19
	Power / W	513.79	515.74
	T_{VL} / °C	52.6	52.0
	T_{bath} / °C	-	54.4
2500	Speed / rpm	2503.7	2501.2
	Torque / N·m	2.23	2.27
	Power / W	584.03	594.08
	T_{VL} / °C	53.4	53.4
	T_{bath} / °C	-	55.9

Table B.42: Standard deviation of the second experimental results for pinion power loss results with rolling bearings in overflow.

Speed rpm	Variable	Test	
		Rolling Bearing	Pinion + Rolling Bearing
500	Speed / rpm	1.6	1.4
	Torque / N·m	0.26	0.29
	Power / W	13.60	15.02
750	Speed / rpm	1.3	1.5
	Torque / N·m	0.32	0.35
	Power / W	25.03	27.29
1000	Speed / rpm	1.3	1.4
	Torque / N·m	0.20	0.20
	Power / W	20.60	21.00
1500	Speed / rpm	1.4	1.4
	Torque / N·m	0.21	0.21
	Power / W	33.35	32.36
2000	Speed / rpm	1.6	1.2
	Torque / N·m	0.28	0.29
	Power / W	58.46	60.35
2250	Speed / rpm	1.5	2.3
	Torque / N·m	0.37	0.33
	Power / W	87.51	78.66
2500	Speed / rpm	1.7	1.9
	Torque / N·m	0.50	0.52
	Power / W	132.16	136.17

C Additional Experimental Tests

C.1 Experimental results

As it is not possible to control flow rate and oil leaving temperature of the thermostatic bath, there is a necessity of modulate this parameters depending on the oil bath temperature. The flow rate of this pump system depends on the pressure drop of delivery system, each depends of the oil viscosity. Therefore exist the necessity of understand the oil flow rate and leaving temperature dependence of the bath temperature. So the flow rate will be modulate for the different temperatures that the tests will be realised, as well the oil leaving temperature.

Now it is possible to begin the experimental work in the rear axle. First it will be realised a experimental test to obtain the pinion rolling bearings power loss, therefore an oil circulation system will be used to lubricate the pinion rolling bearings and the test will be realised using the test parameters previously presented. Then the experimental tests will be done using sump lubrication, so it is possible to obtain the losses of the pinion rolling bearings plus the pinion churning losses. This will allow to subtract the pinion rolling bearings losses, obtaining the pinion churning losses.

To conclude, the crown wheel will be assembled and the test will be performed. To this results, the pinion churning plus rolling bearings losses can be subtracted, obtaining the crown wheel plus rolling bearings power losses. It will not be possible to separate this losses, due to the complexity of the assembly.

C.1.1 Oil Volumetric Flow Rate vs Temperature

In order to understand the oil volumetric flow rate, provided by the thermostatic bath presented in Figure 5.5, during power loss tests, some experimental tests were performed. This way it is possible to adapt a model that relate the oil volumetric flow rate with the oil temperature at the differential. As the result of the high variation of the viscosity of the oil with the temperature, the flow rate for the same oil pump will not be the same for different temperatures. With this test, it was also possible to understand the temperature drop between the oil bath and the oil that arrive in the rolling bearing, being easy to set the temperature at the rolling bearing during the power loss test.

To do this experiment, the oil temperature at end of the hose will be set at the chosen temperatures, presented in Table 5.3. When the temperature stabilizes, a 300 ml goblet the time that took to fill it up was taken. With this data, it was possible to obtain the volumetric flow rate at the chosen temperature and understand the temperature drop over.

During this experimental test, it was possible to visualize the necessity of temperature stabilisation in the oil pump and all other components that conduct the oil to the differential. So the tests with a 15 min pause between each other were done, in order to obtain stabilized temperatures in all components and the obtained results are represented in Figure C.1.

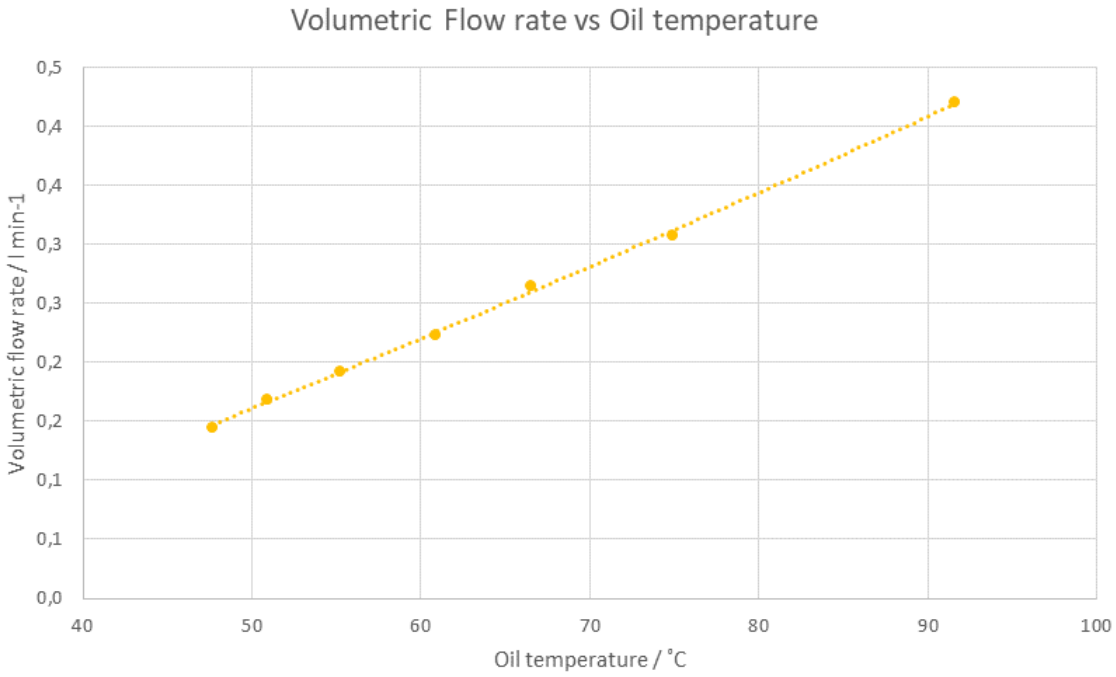


Figure C.1: Oil flow rate vs temperature.

With the data from this test, it was also possible to obtain a relation between the oil bath and the oil at the rolling bearing temperature, presented in Figure C.2. The linear relation between the oil bath and rolling bearing oil sump temperature can be used ease the process of setting up the oil temperature exit at the rolling bearings. It should be noted that what is controlled is the oil bath temperature.

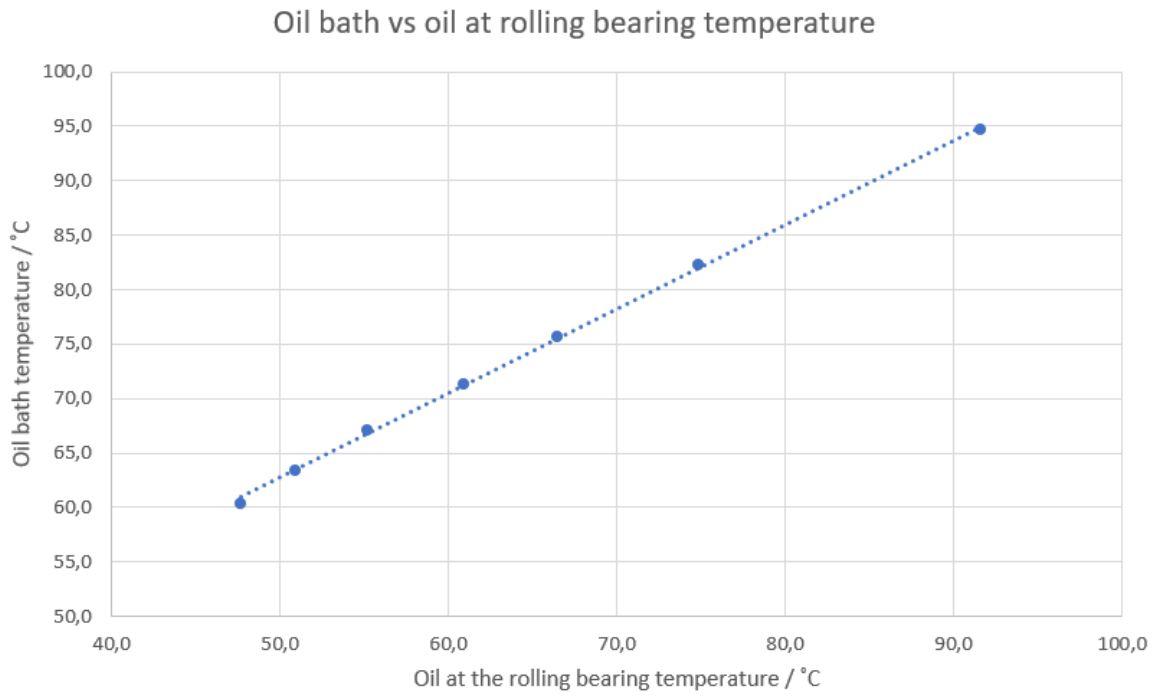


Figure C.2: Oil bath vs rolling bearing exit temperature.

C.1.2 Rolling Bearings Power Loss results - First Test

In order to understand the power losses over the pinion rolling bearings, for different conditions of temperature and rotational speed, some experimental tests in the differential were done with only the pinion mounted. Because it is necessary to obtain just the power loss of the rolling bearings, it was decided to use oil injection lubrication over the channel that exists between the rolling bearings of the pinion, as it is possible to see in Figure C.4. This way, the differential sump can be dry, therefore there will not be churning power loss due to the pinion movement. The considered oil temperature was measured and controlled at the end of the oil injection hose, as shown in Figure C.4.

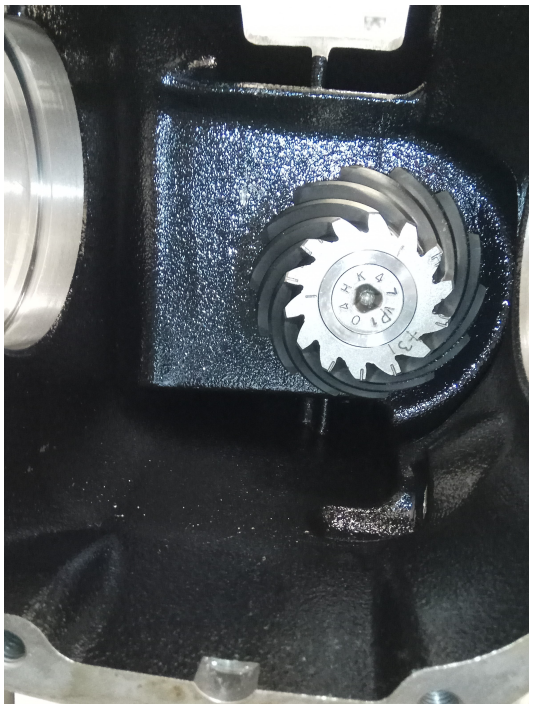


Figure C.3: Differential pinion.

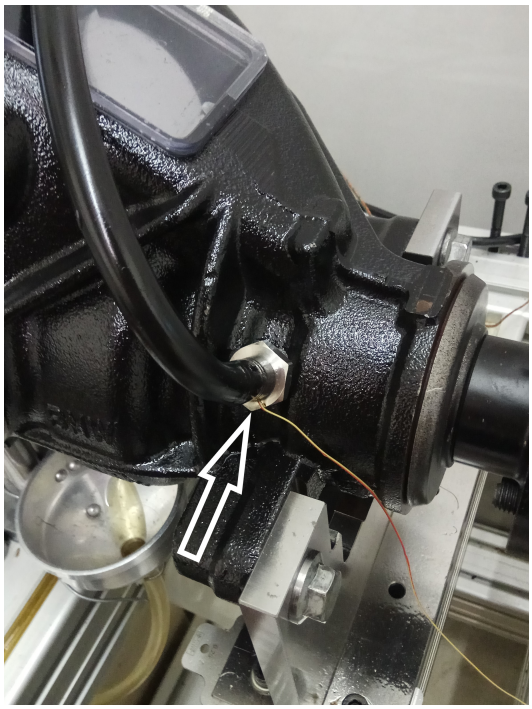


Figure C.4: Oil injection point.

For this experimental test, the chosen rotational speeds and oil temperatures presented in chapter 5.2 were used. It was realized that the most efficient way that the most efficient way to perform this analysis, was to set an oil temperature and run all the speeds, because of the necessity of oil temperature stabilization. So between each speed, it was set a minute pause and fifteen minutes between each temperature. Each test was repeated three times, in order to rule out any chance of using anomalous results.

In Figure C.5, the average results of torque loss obtain in function of the speed for the different temperatures are presented.

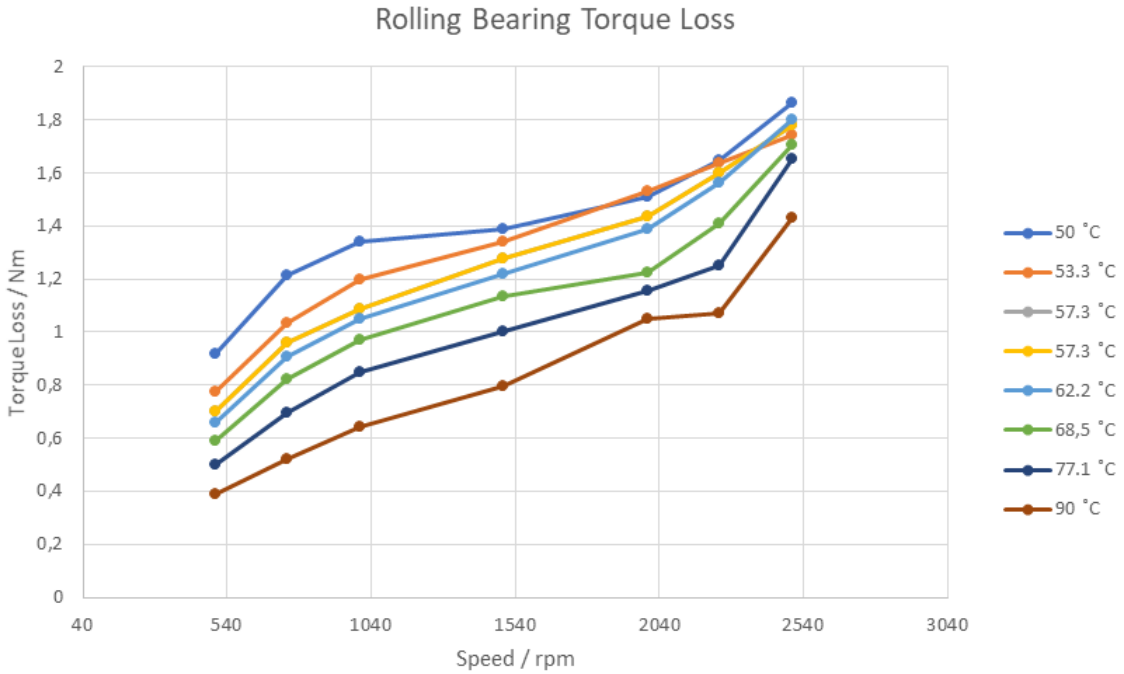
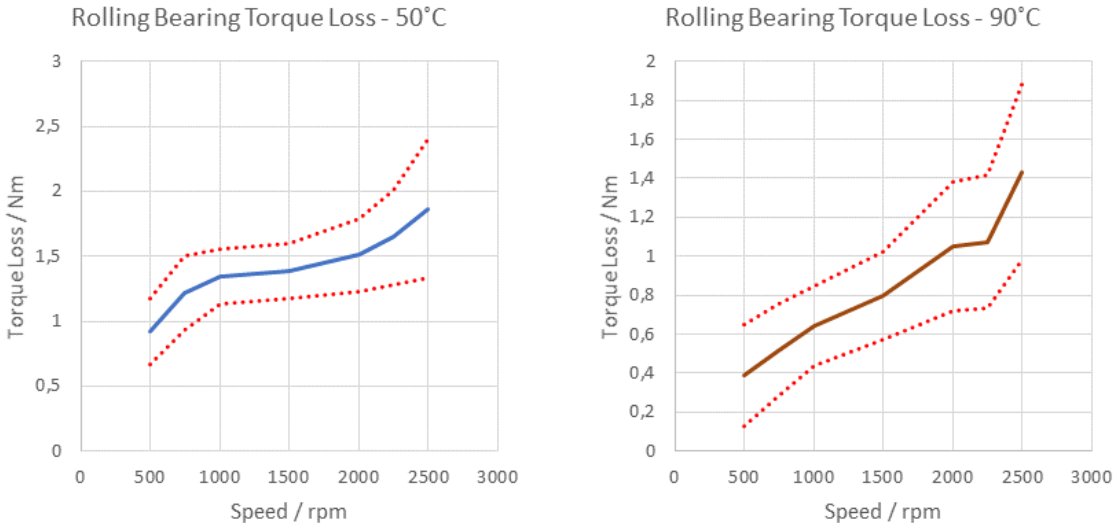


Figure C.5: Torque loss vs rotational speed of the first test for the pinion rolling bearings.

As expected, it is possible to verify the influence of the oil temperature over the power loss, due to the increase of the oil flow rate and decrease of the oil viscosity with the temperature. At this moment, it is an early stage to take any conclusion about the power losses that were obtained.

In Figure C.6, it is possible to analyse the standard derivation of the values that were measured for different temperatures. This way, we can evaluate the range of results that were obtained experimentally. It can also be observed an unusual increase of the torque loss from 2250 to 2500 rpm, especially at higher temperatures, that can be explained by the possible oil starvation that is felt for higher rotational speeds.



(a) 50°C. **(b)** 90°C.

Figure C.6: Rolling bearing torque loss for different oil temperatures.

C.1.3 Pinion and Rolling Bearings Power Loss results - First Test

After the first tests where the pinion rolling bearings losses were evaluated, it was necessary to evaluate the pinion power losses caused by the drag between the oil and pinion surfaces. Because it is not possible to obtain just the churning losses, the previously measured rolling bearing losses must subtract to the combined pinion and rolling bearings losses.

In order to perform this experiment, the oil level in the differential was set to the level recommended by the manufacturer. This way, it was possible to assure that the rolling bearings lubrication was adequate and verify the increase in the power losses due to the pinion churning losses, when comparing to the measurements reported in the section C.1.2. This test already been presented in chapter 5.3.2.

The results from these tests are presented Figure C.7. In these charts, when the chart line is made of dots, it means that the oil bath temperature rise above the defined temperature.

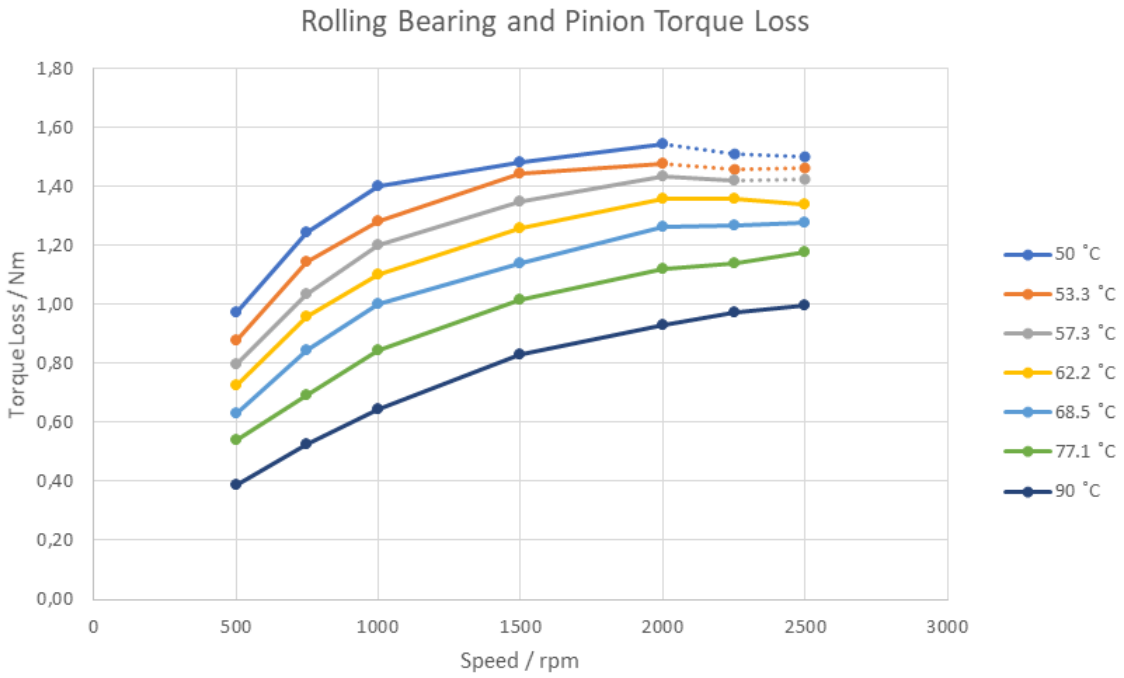


Figure C.7: Rolling bearing and churning torque loss vs rotational speed of the first test.

Interpolating the power loss results for the rolling bearings with the measured oil temperature at the rolling bearings during the pinion and rolling bearing tests and then subtracting these results, it is possible to obtain an estimation of the pinion churning losses.

After analyzing the pinion power loss results, it is possible to conclude that something is wrong, because of the negative power loss results that were obtained for some speeds and temperatures. After giving some though to such results, the possibility of insufficient oil flow rate in the rolling bearing tests is most likely cause.

The solution that was proposed was to fill the sump with oil, assuring that the oil level do not reaches the pinion. So the rolling bearings will be sump lubricated at a lower level, but with the guarantee that the oil will not touch the rotating pinion, hoping to obtain better results.

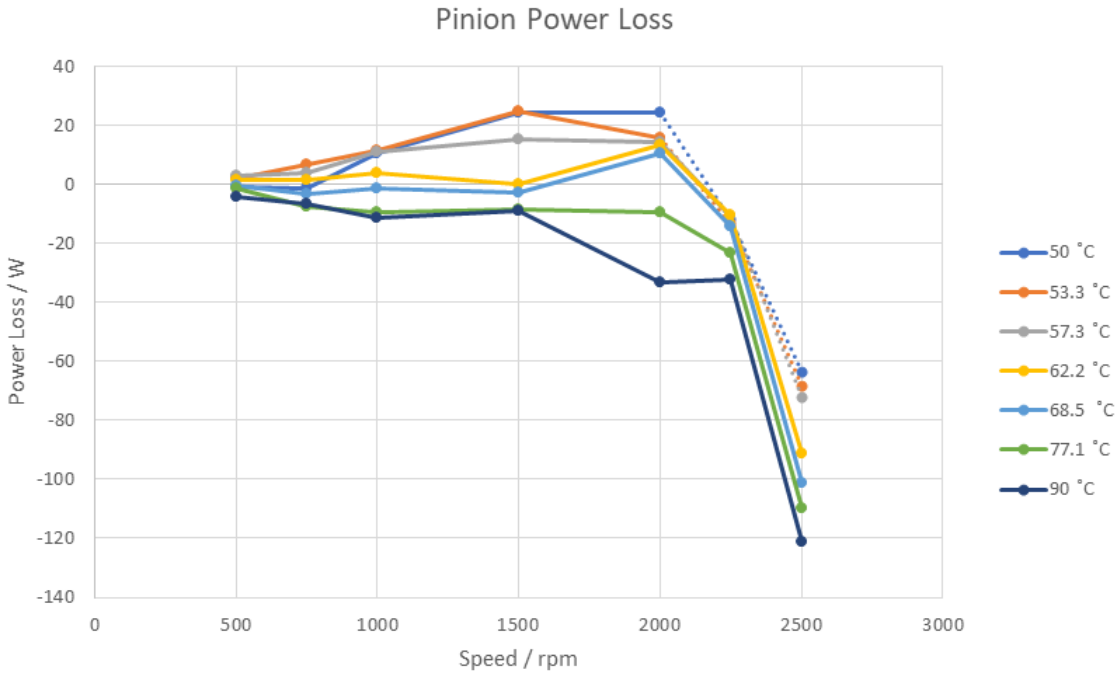


Figure C.8: Pinion power loss vs rotational speed of the first rolling bearing test.

C.1.4 Rolling Bearings Power Loss results - Second Test

As explained in the previous chapter, there is a suspicion of insufficient lubrication in the rolling bearings during the tests presented in chapter C.1.2. Therefore this time, the differential will be filled with oil, assuring that oil level does not reaches the pinion, so that the churning losses in the pinion are eliminated, while keeping the rolling bearings sump lubricated. Maintaining the same test parameters, it was possible to obtain the results presented in Figure C.9.

Now using the new results of the rolling bearing power loss and applying the same technique to interpolate the results, explained in the previous chapter, the new results are presented in Figure C.10.

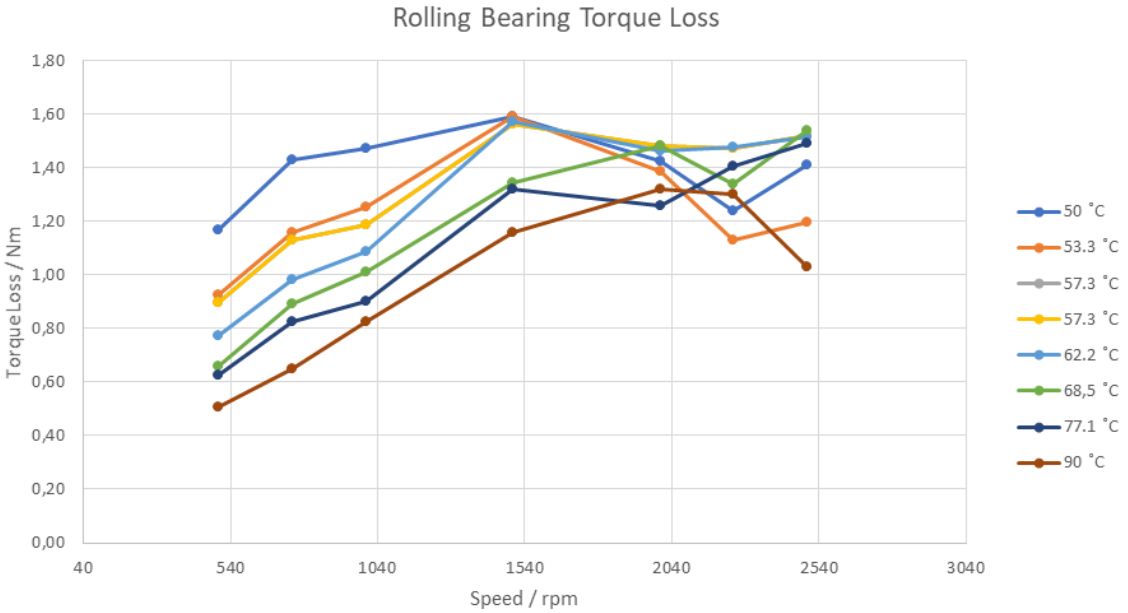


Figure C.9: Torque loss vs rotational speed of the second test for the pinion rolling bearings.

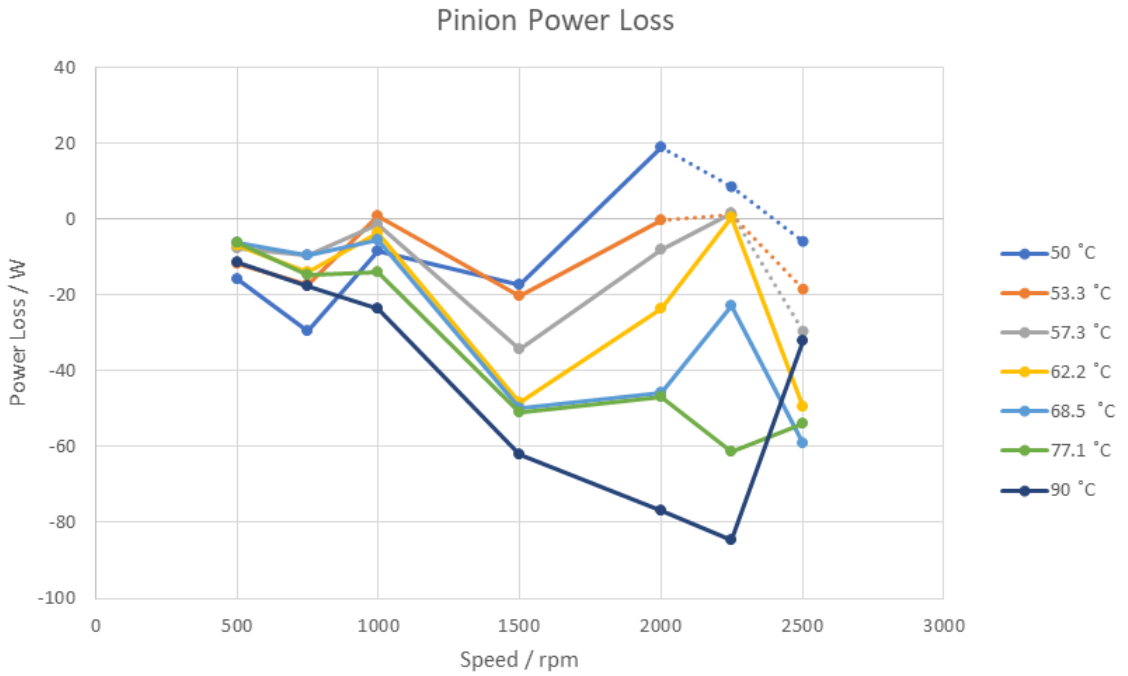


Figure C.10: Pinion power loss vs rotational speed of the second rolling bearing test.

After analysing the new pinion results, it is possible to conclude that this is not a viable option and the results for the pinion power loss are still wrong, due to oil

starvation. As observed in Figure C.11, the oil level does not reach the rolling bearings, explaining the oil starvation problems. As it can be verified in Figure C.12, in this test, better results were obtained for high velocities and worst results for lower velocities. This means that in almost every condition that was tested, negative results were obtained for the pinion power loss and it stills have insufficient lubrication. This test was only repeated once, as it was possible to concluded that it did not work well, therefore there is no necessity to repeat it.

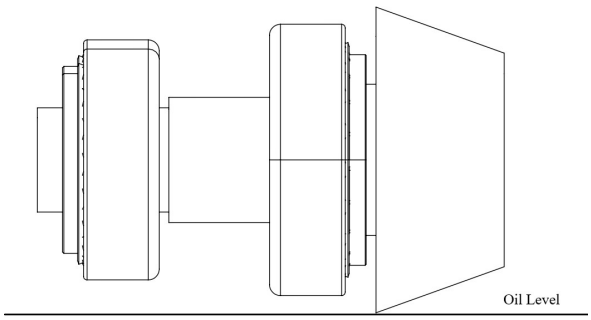
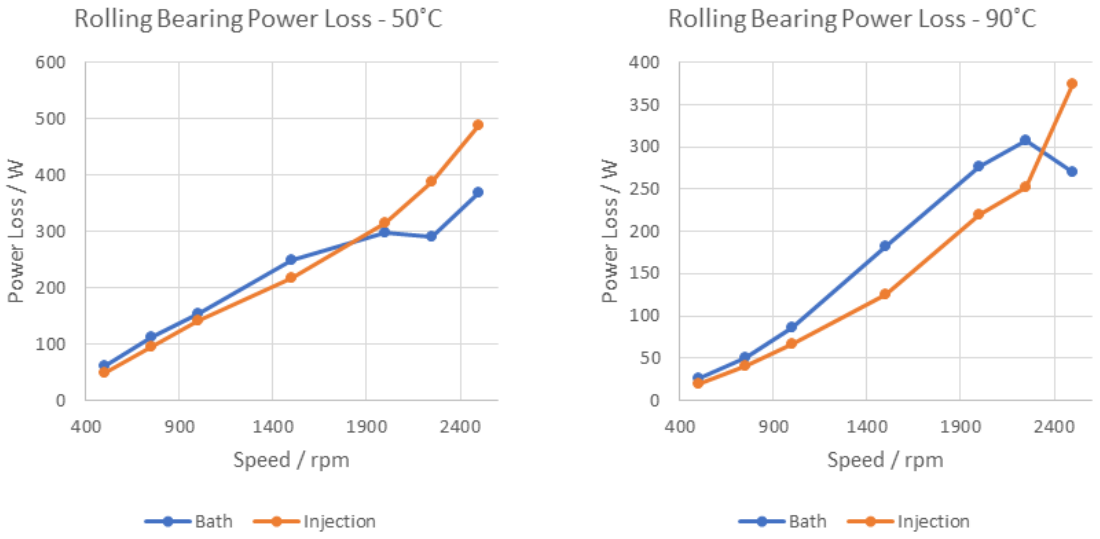


Figure C.11: Oil level schematic drawing.



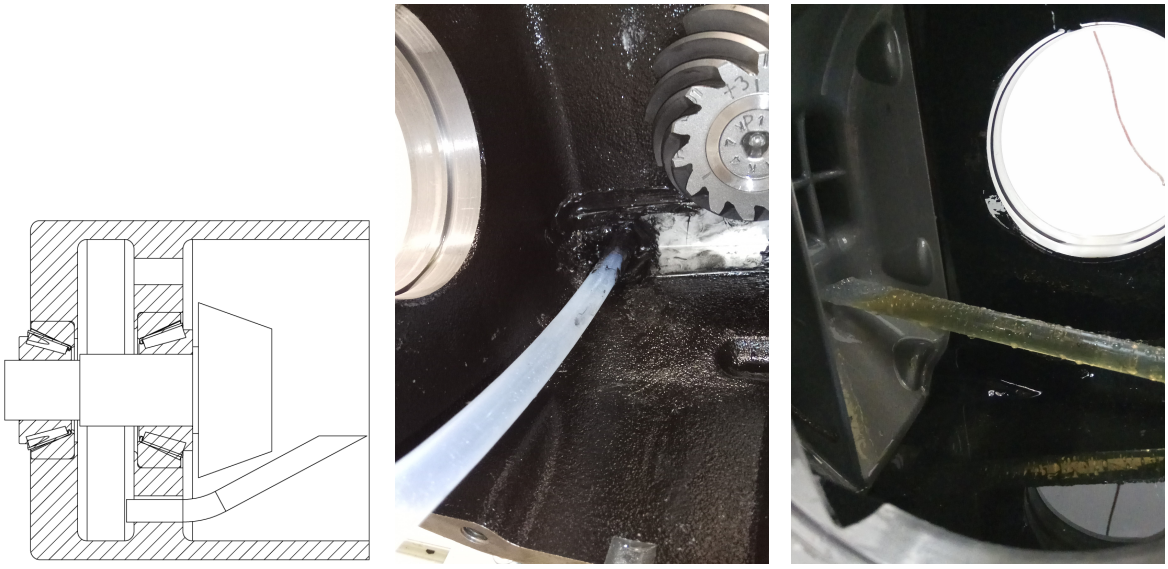
(a) 50°C. **(b)** 90°C.

Figure C.12: Results comparison of rolling bearing torque loss for different oil temperatures.

C.1.5 Rolling Bearings Power Loss results - Third Test

In order to solve the problem of insufficient lubrication, a new solution was proposed. This time, the oil level proposed by the manufacturer was forced, but

just inside the pinion rolling bearings chamber. The idea was to plug the bottom oil channel, just leaving an hole for an hose. This hose will be sealed in the plug and the other tip will be elevated up to the manufacturer oil level, as shown in Figure C.13. The plug is made of aluminium sheet, a very easy material to form into the necessary shapes to plug the oil exit and an high temperature silicon was used to assure the sealing between the surfaces.



(a) Schematic drawing. **(b)** Front view. **(c)** Side view.

Figure C.13: Assembly that forces the oil inside the rolling bearing chamber.

Unfortunately, this assembly did not perform as expected. The rolling bearing can not provide sufficient restriction to assure the oil level during the test for the possible oil pump flow rate. However, it was possible to verify that the speed and temperature played a role in the amount of oil that could flow though the front rolling bearing, Figure C.13a.

Due to the nature of this setup, it could be assured that the oil was passing through the pinion rolling bearings. Hopping to obtain better results, the experiments were continued and the new average data of the three test is presented in Figures C.14 and C.15.

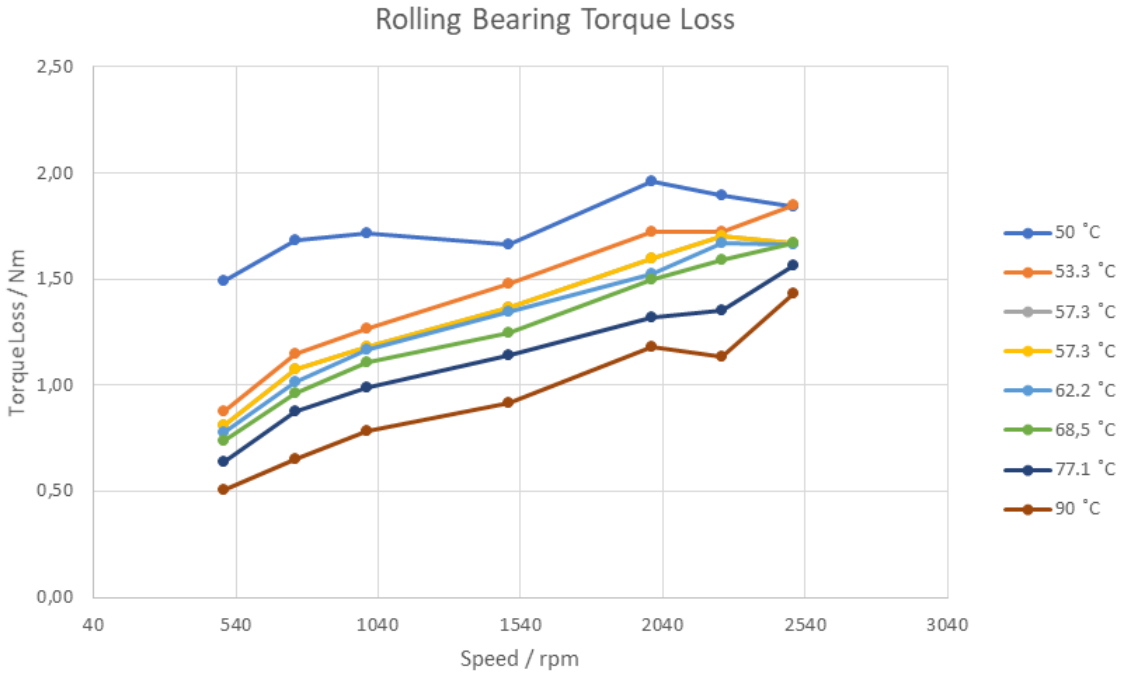


Figure C.14: Torque loss vs rotational speed of the third test for the pinion rolling bearings.

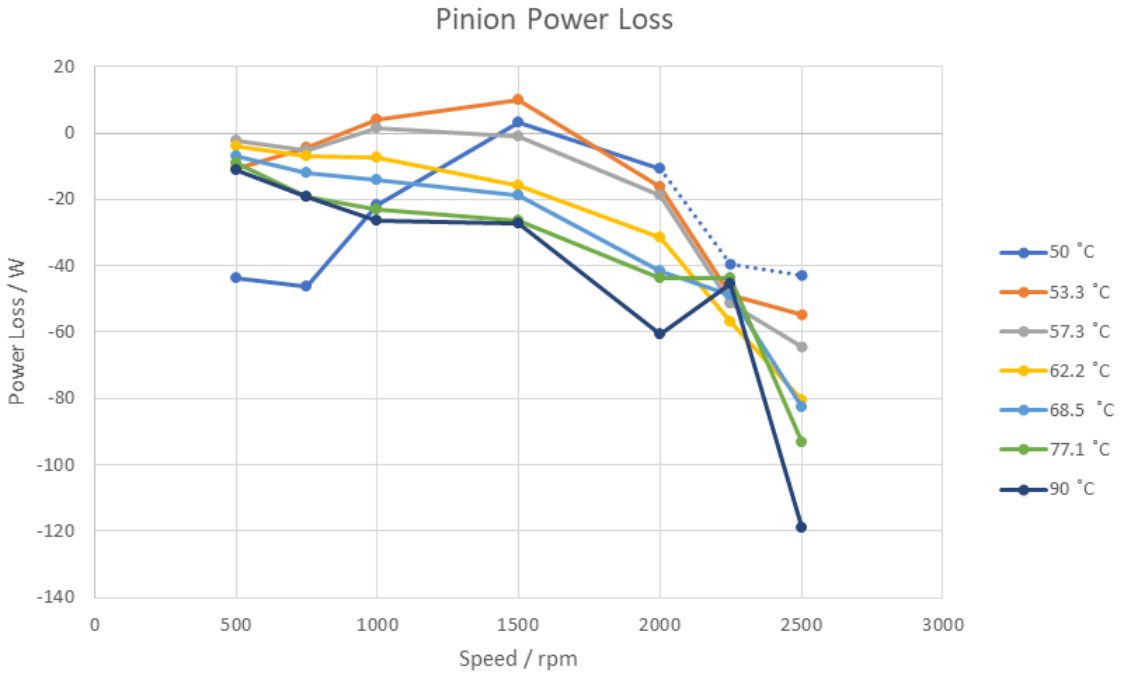
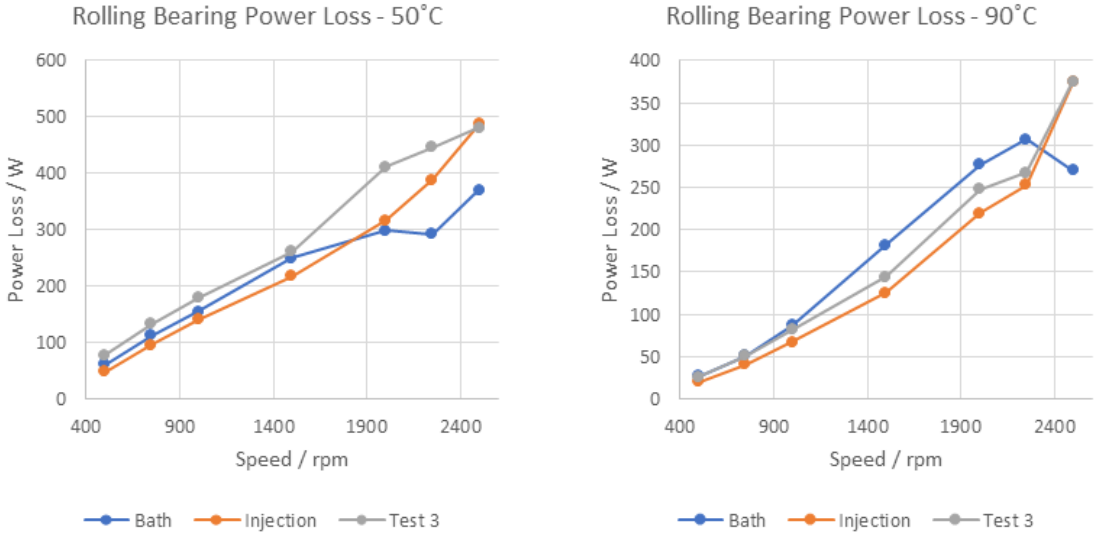


Figure C.15: Pinion power loss vs rotational speed of the third rolling bearing test.

From Figures C.14 and C.15, it is possible to conclude that the lubrication con-

ditions for the sump lubricated pinion + rolling bearings tests could not yet be matched. At this point, it was possible to observe in Figure C.16 that the results for the current test, the oil bath and the injection test without the channel plug yield close power loss results.

During the test, it was possible to verify that, when the velocity is around 750 rpm and the temperature 90 °C, the hose connected to the hole in the plug plate indicates an oil level similar to that proposed by the manufacturer, yet the difference between the measured pinion + rolling bearings and the results from the current test is still negative.



(a) 50°C. **(b)** 90°C.

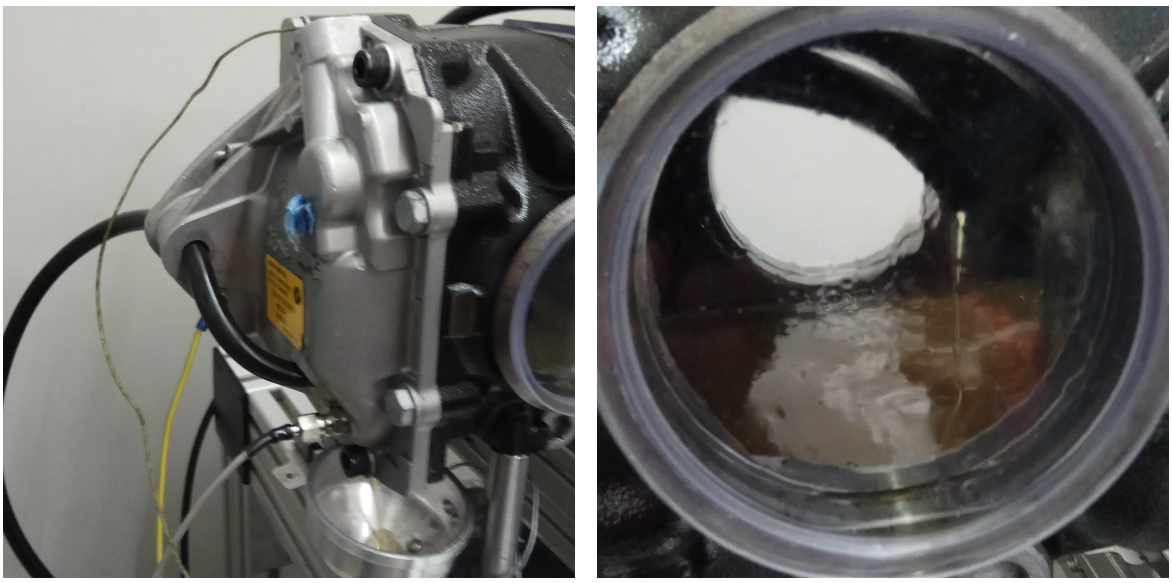
Figure C.16: Results comparison of rolling bearing torque loss for different oil temperatures.

C.1.6 Pinion and Rolling Bearing Power Loss results - Second Test

As explained in the previous chapter, there are some suspicious about the first test of the pinion and rolling bearing power loss. After inspecting the differential, it was thought that this problem could be caused by heating element, that is located near the bottom of the differential sump and is long enough to run for the entire length of the differential even going through the bottom channel that opens into the rolling bearings lubrication chamber. There was a possibility that this could cause an overheating of the oil in this chamber and the rolling bearings, leading to an uneven temperature in the different zones of the differential. This could lead to an better efficiency of the rolling bearing caused by the lower oil viscosity in this area.

In order to solve this problem, the heating element was removed and the ther-

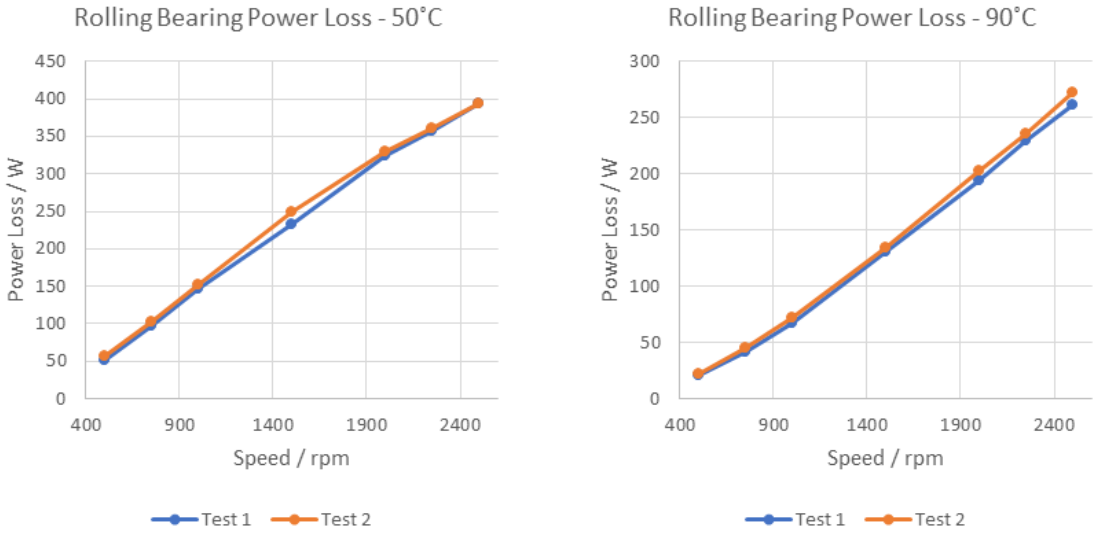
mostatic bath was used to heat the oil, as it can be observed in Figure C.17. The idea was to leave the oil flowing through the differential and the oil level plug open, letting the excess oil return to the bath, assuring an uniform oil temperature inside the differential.



(a) Outside view. **(b)** Inside view.

Figure C.17: Second test assembly of the pinion and rolling bearing.

In Figure C.18, the differences between the first and second test of the pinion and rolling bearing power loss can be verified. The difference between the results is marginal and down to measurement error, which allowed to rule out the initial possibility. With this results it was also possible to verify that the fact that the rolling bearing chamber is now closed, does not have any effect in the rolling bearing power loss.

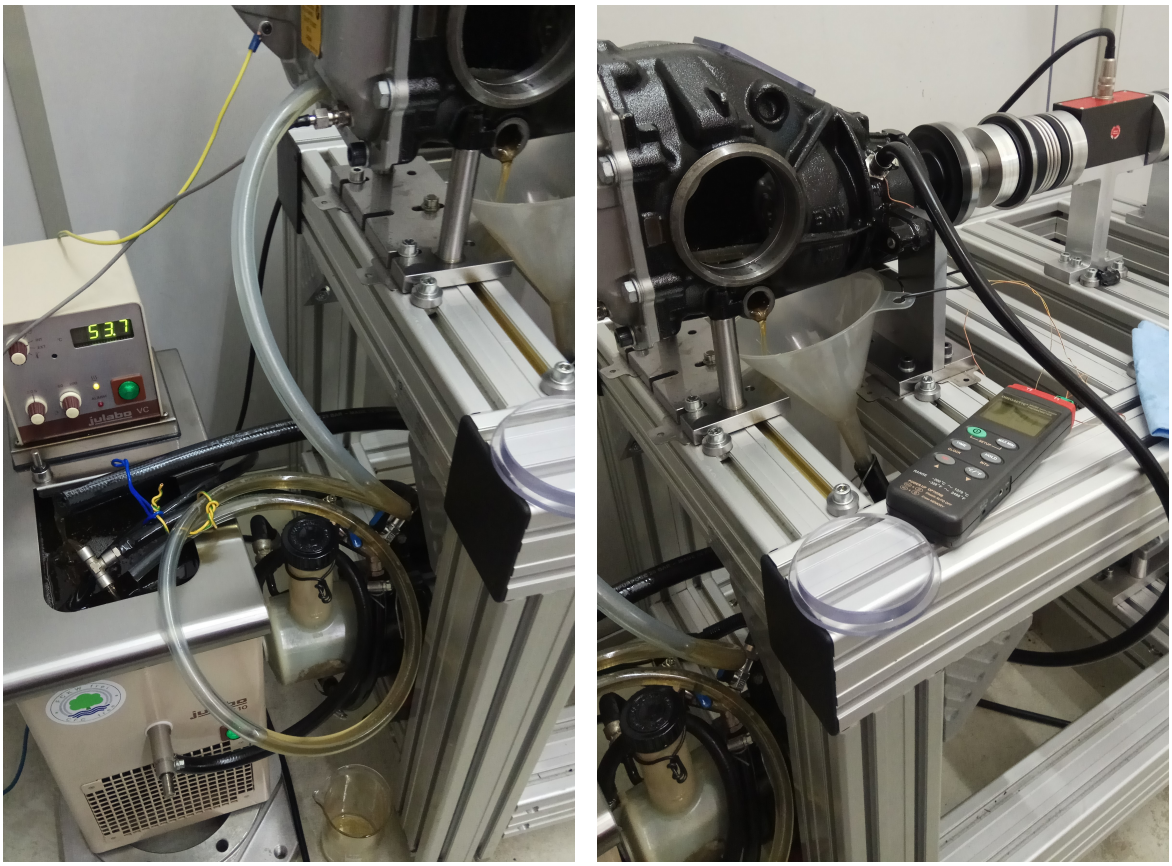


(a) 50°C. **(b)** 90°C.

Figure C.18: Results comparison of pinion and rolling bearing torque loss for different oil temperatures.

C.1.7 Rolling Bearing Power Loss results - Fourth test

After concluding that there is no problem with the results from the first test of the pinion and rolling bearings, we return to assume that the problem is the rolling bearings test. As explained in chapter C.1.5, we suspect that the problem is the insufficient oil flow rate provided by the pump, therefore for this test, we will install an hydraulic pump capable of debit more flow rate, as it is possible to see in Figure C.19. To perform this experiment, there was a necessity of applying a bypass valve, so that there is a possibility of adjusting the flow rate that went into the rolling bearings chamber. The oil temperature was still assured by the oil thermostatic bath.

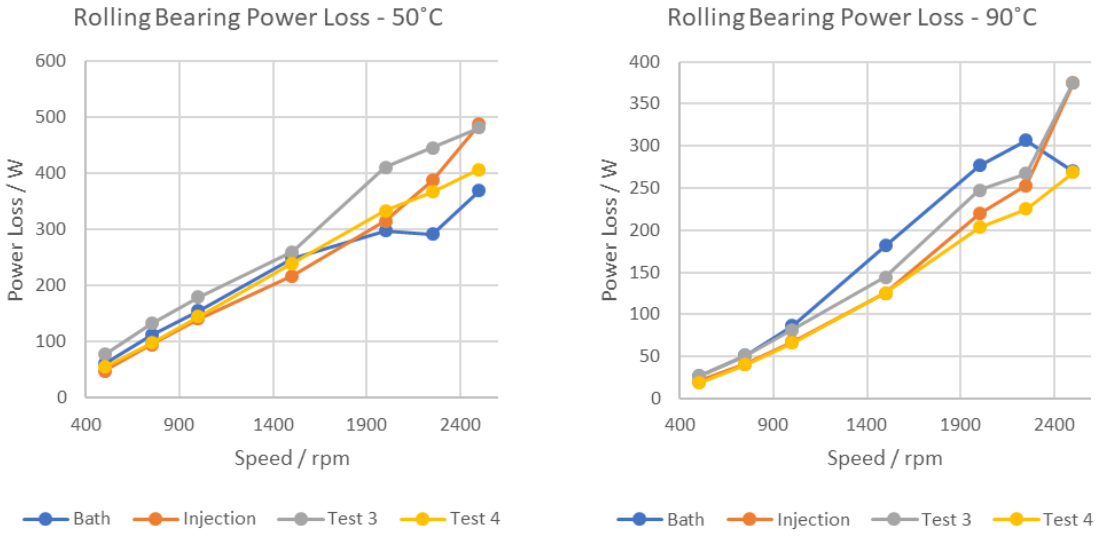


(a) Oil thermostatic bath. **(b)** Differential.

Figure C.19: Fourth test assembly of the rolling bearing.

According to the results presented in Figure C.20, it is possible to verify that the results are practically the same except at high rotational speeds, were there appears to be an improvement. This can only means that it is very difficult to simulate the oil bath lubrication with an circulating oil system.

There is a suspicion that the motion of the oil induced by the rotation of the shaft creates some pressure on the corner of the chamber. This could provide a wrong measurement of the oil level inside the chamber, as it will show level plus the increase of pressure that is felt in this point that the tube is placed.



(a) 50°C. **(b)** 90°C.

Figure C.20: Results comparison of pinion and rolling bearing torque loss for different oil temperatures.

In Figure C.21, it is possible to visualize the oil flow rate that was consumed by the rolling bearings for different temperatures and speeds. In order realise this flow rate measurement, it was necessary to assure that the oil flowing from the hose and the rolling bearings do not combine. Therefore to the hose was extended up to to the thermostatic bath, leaving just the oil from the rolling bearings coming out through the differential plug, as observed in Figure C.19. This allowed to perform that same procedure presented in chapter C.1.1, where the time that took to fill it up a 300 ml goblet was taken, with the oil coming from the differential plug. With this information it is possible to analyse the influence of the oil viscosity and rolling bearing speed over the oil flow.

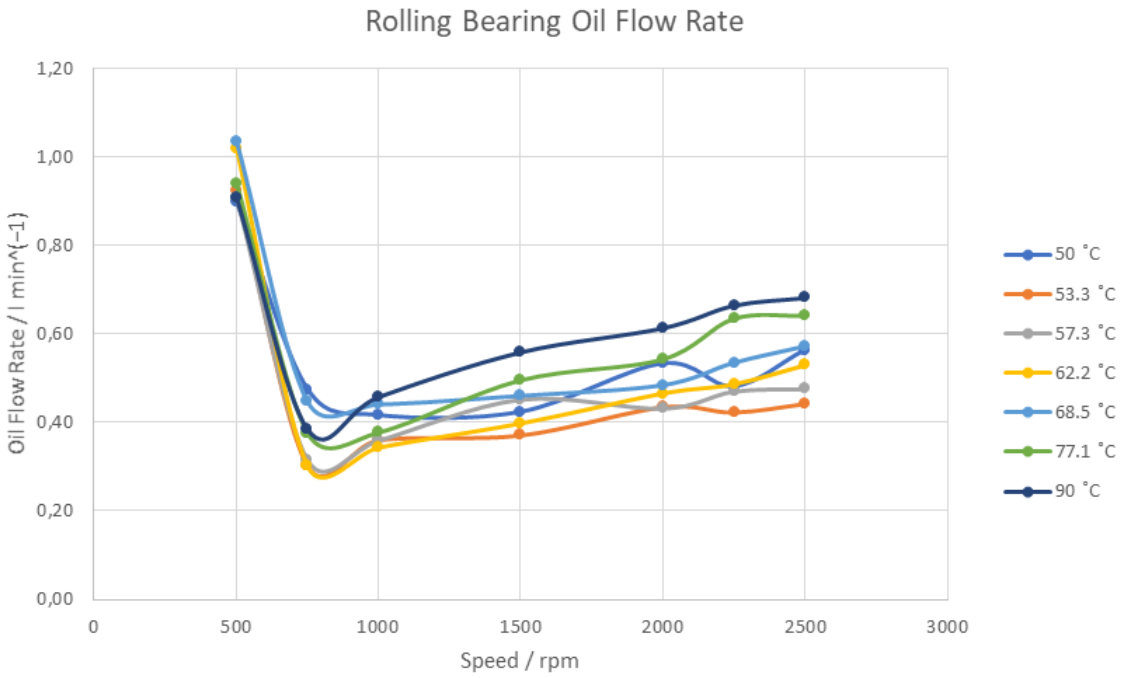


Figure C.21: Oil flow rate consumption.

C.1.8 Rolling Bearing Power Loss results - Fifth test

In order to understand this lubrication phenomenon, it was decided to run the test for different oil rate flows. This could let to discover the influence of the oil flow rate over the rolling bearings and weather there is or not a problem of overflow or starvation. It was also decided to do some tests for two different temperatures and analyse the results. In Figures C.22 and C.23, it is possible to analyze the obtained results from these tests. In order to have a better reference point, it was decided to use the pinion and rolling bearings test and compare with the results. It is known that the power loss of the rolling bearings alone should be lower than that of the arrangement including the pinion.

After analysing the results, it was possible to conclude that is a problem of overflow and with an oil flow rate of 0.3 l min^{-1} the results are better. So it was decided to repeat the rolling bearings tests providing the 0.3 l min^{-1} flow rate.

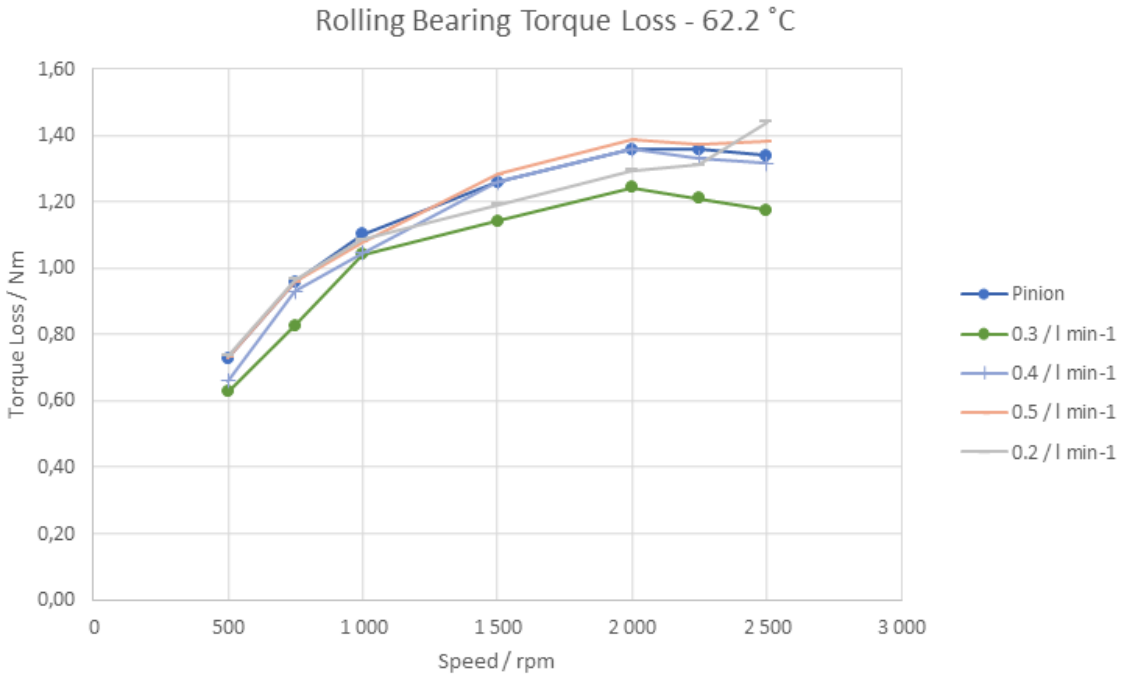


Figure C.22: Torque loss for different flows at 62.2°C.

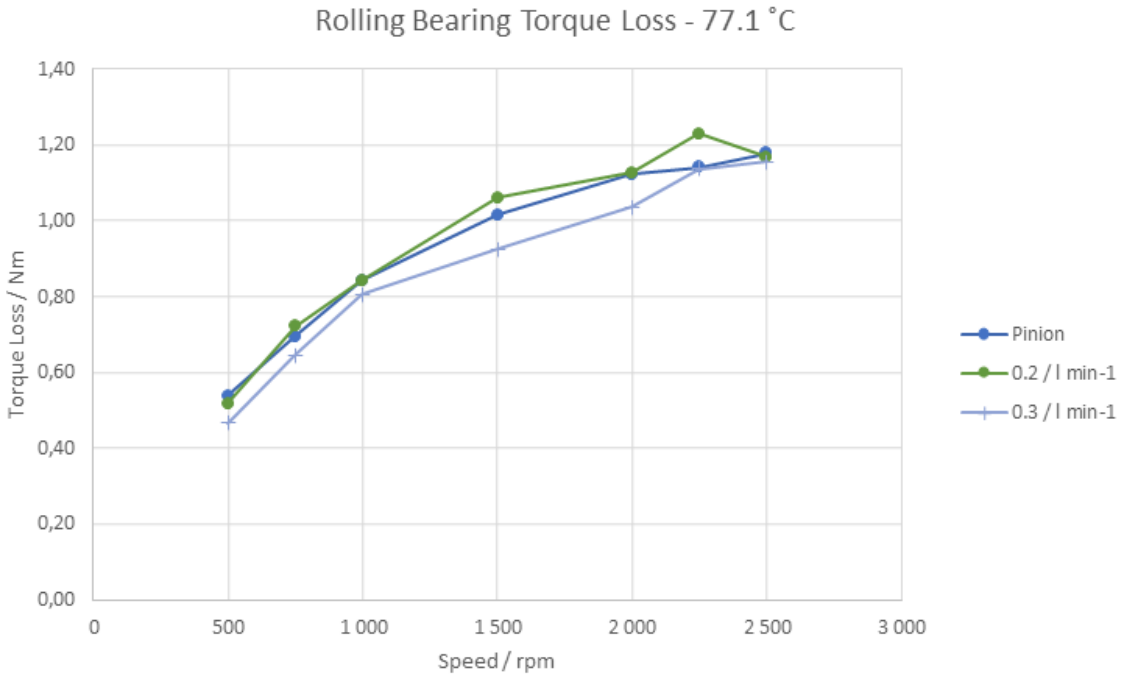
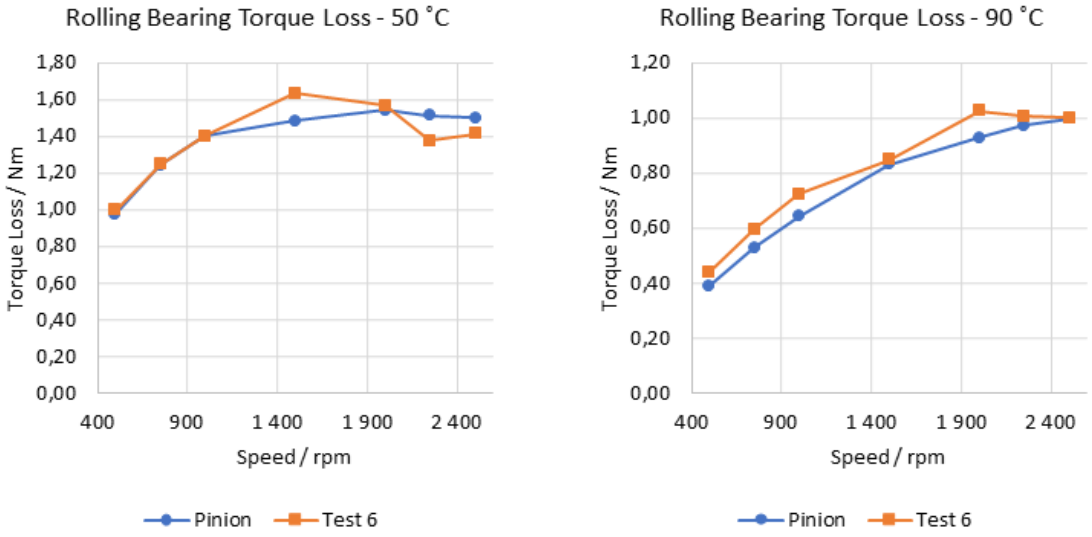


Figure C.23: Torque loss for different flows at 77.1°C.

C.1.9 Rolling Bearing Power Loss results - Sixth test

With the flow rate defined on the previous chapter, the tests were repeated aiming to obtain the lowest power loss for the rolling bearings. The test was performed in the usual conditions with a constant oil flow rate of 0.3 l min^{-1}. In Figure C.24, it is possible to analyze the obtained results, where it is presented both the pinion and the rolling bearing results, in order to realise a comparative analysis.



(a) 50°C. **(b)** 90°C.

Figure C.24: Results comparison of pinion and rolling bearing torque loss for different oil temperatures.

It is now possible to conclude that the ideal oil flow rate for each operating condition must be found. It is also important to notice that we do not have consistent results when in comparison with the fifth test for the same temperature. So we should have a preheating of the system before initiating the test, making sure that the temperature stabilised for all the components.

C.1.10 Rolling Bearing Power Loss results - Seventh test

As performing a test in order to find the ideal oil flow rate for each condition is a lengthy process, the SKF information regarding the necessary oil flow rate for the proper lubrication was checked. According to SKF [15], when the oil level H is known when oil is flowing and the rolling bearings is at stand-still with oil jet lubrication, this H value can be used in the oil bath model to obtain an estimation for the oil jet churning losses. So the oil flow rate was set with the bearing stand-still making sure to have the right oil level H, as recommended by the differential

manufacturer. Then the tests were run with constant flow rate through the different speeds and define a different flow rate for each temperature.

During the first test, an increase of the temperature was observed at higher rotational speeds, due to the starvation of lubrication. This way it was decided not to carry on with the experiments in order to not damaged the rolling bearings.

In Figure C.25, it is possible to visualize the obtained results for 50°C in comparison with the pinion results. As the speed goes up, the temperature and the respective torque loss have also increased.

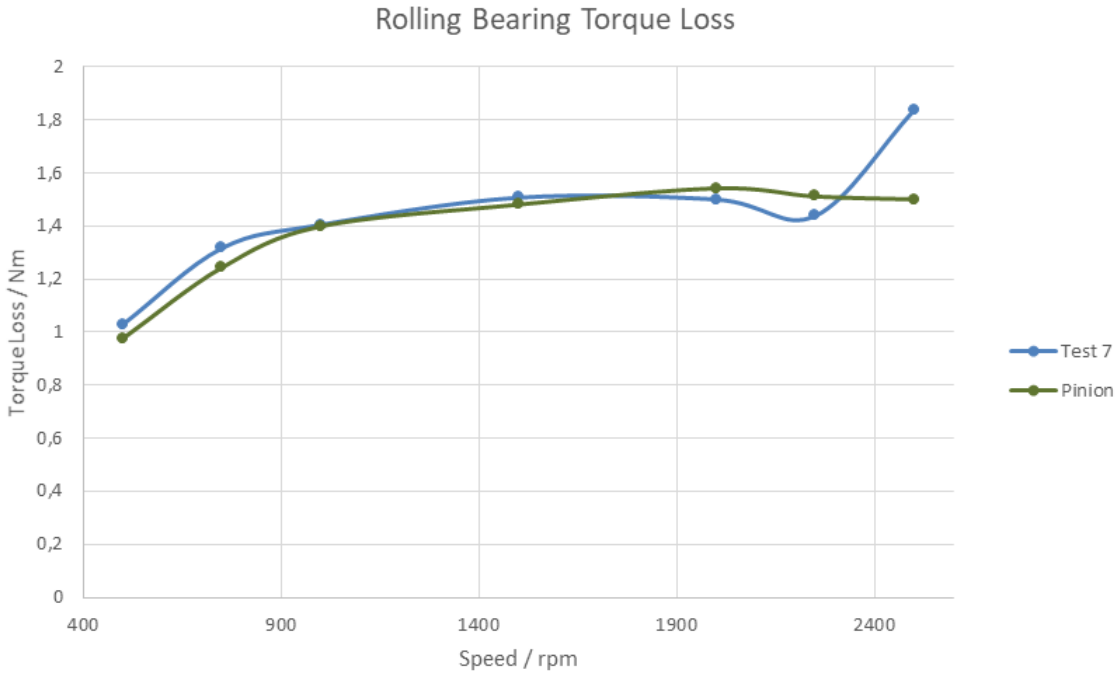


Figure C.25: Torque loss at 50°C with constant flow rate.

C.2 Experimental Datasheets

C.2.1 Oil Volumetric Flow Rate results

Table C.1: First experimental results of oil temperature vs volumetric flow rate.

T_{des} / °C	T_{VL} / °C	T_{bath} / °C	Q / l min^{-1}
50.0	50.1	59.4	0.19
50.0	49.5	59.1	0.19
50.0	50.2	60.0	0.19
53.3	53.2	63.1	0.22
53.3	52.2	63.9	0.21
53.3	53.2	63.6	0.22
57.3	56.5	68.3	0.23
57.3	57.1	69.1	0.24
57.3	58.3	68.4	0.23
62.2	61.5	73.4	0.27
62.2	62.0	73.5	0.27
62.2	62.3	73.4	0.27
68.5	70.1	77.7	0.37
68.5	70.8	77.6	0.35
68.5	67.9	77.1	0.34
77.1	77.4	80.2	0.50
77.1	77.6	80.5	0.49
77.1	77.8	80.4	0.48
90.0	89.9	93.9	0.38
90.0	90.5	93.9	0.39
90.0	91.9	94.4	0.38
77.1	76.1	84.0	0.24
77.1	78.1	84.0	0.24
77.1	78.3	84.0	0.23

Table C.2: Second experimental results of oil temperature vs volumetric flow rate.

T_{des} / °C	T_{VL} / °C	T_{bath} / °C	Q / l min^{-1}
50.0	46.7	56.5	0.14
53.3	52.1	61.6	0.18
57.3	58.6	65.7	0.21
62.2	60.2	68.2	0.23
68.5	66.3	71.9	0.26
77.1	74.3	77.9	0.32
83.1	80.3	81.7	0.37
90.0	90.9	93.0	0.47

Table C.3: Third experimental results of oil temperature vs volumetric flow rate.

T_{des} / °C	T_{VL} / °C	T_{bath} / °C	Q / ml s^{-1}
50.0	47,7	60,3	0.14
53.3	50,9	63,4	0.17
57.3	55,2	67,1	0.19
62.2	60,9	71,3	0.22
68.5	66,5	75,7	0.26
77.1	74,9	82,2	0.31
83.1	91,6	94,6	0.42

C.2.2 Rolling Bearings Power Loss results - First Test

Table C.4: First experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.7	499.4	499.5	499.2	499.2	499.4	500.6
	Torque / N·m	0.91	0.81	0.7	0.66	0.59	0.49	0.37
	Power / W	47.94	42.29	36.46	34.41	30.89	25.73	19.64
	T_{VL} / °C	50.0	53.4	57.4	62.3	68.6	77.3	90.0
750	Speed / rpm	748.1	747.0	748.9	749.0	746.7	749.5	745.8
	Torque / N·m	1.20	1.07	0.97	0.93	0.83	0.70	0.51
	Power / W	93.79	83.96	75.96	72.68	64.81	55.08	40.20
	T_{VL} / °C	49.6	53.2	57.2	62.2	68.5	77.2	89.8
1000	Speed / rpm	1001.7	997.4	996.9	999.1	996.5	996.4	995.9
	Torque / N·m	1.32	1.22	1.10	1.06	0.97	0.84	0.64
	Power / W	138.22	127.45	115.33	111.11	101.30	87.55	66.52
	T_{VL} / °C	50.1	53.3	57.3	62.1	68.5	77.2	89.7
1500	Speed / rpm	1502.3	1501.5	1501.3	1500.8	1499.7	1499.7	1498.3
	Torque / N·m	1.37	1.32	1.26	1.23	1.13	0.98	0.80
	Power / W	215.63	208.08	198.57	192.90	177.24	153.33	125.08
	T_{VL} / °C	50.3	53.3	57.3	62.2	68.7	77.3	89.8
2000	Speed / rpm	2000.0	1998.3	2000.3	1997.2	2000.0	2000.2	1999.6
	Torque / N·m	1.35	1.45	1.49	1.44	1.17	1.11	1.11
	Power / W	283.07	304.09	312.81	300.60	245.22	232.58	232.41
	T_{VL} / °C	50.2	53.3	57.1	62.1	68.6	77.1	90.2
2250	Speed / rpm	2250.2	2248.2	2250.9	2250.0	2249.8	2449.6	2249.6
	Torque / N·m	1.61	1.64	1.63	1.65	1.47	1.36	1.17
	Power / W	378.40	385.95	383.57	388.64	345.69	319.30	276.04
	T_{VL} / °C	50.2	53.5	57.2	62.0	68.6	77.1	90.1
2500	Speed / rpm	2498.7	2499.5	2501.4	2500.8	2500.9	2500.9	2497.0
	Torque / N·m	1.82	1.85	1.87	1.85	1.79	1.77	1.54
	Power / W	474.91	484.04	488.97	483.44	467.71	462.29	402.92
	T_{VL} / °C	50.3	53.5	57.1	61.9	68.6	77.1	90.1

Table C.5: Standard deviation of the first experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.4	1.6	1.4	1.5	1.4	1.6	1.6
	Torque / N·m	0.25	0.25	0.27	0.26	0.27	0.25	0.25
	Power / W	13.26	13.12	13.89	13.48	13.93	13.26	13.20
750	Speed / rpm	1.5	1.4	1.6	1.3	1.6	1.3	1.9
	Torque / N·m	0.29	0.27	0.29	0.29	0.28	0.24	0.23
	Power / W	22.37	21.01	22.61	22.37	21.93	18.70	17.76
1000	Speed / rpm	1.4	1.4	1.3	1.3	1.7	2.0	1.6
	Torque / N·m	0.21	0.19	0.18	0.20	0.19	0.17	0.18
	Power / W	22.50	19.98	18.68	21.31	19.95	17.92	18.48
1500	Speed / rpm	1.3	1.2	1.1	1.4	1.4	1.2	1.3
	Torque / N·m	0.19	0.18	0.18	0.17	0.21	0.20	0.18
	Power / W	29.43	27.84	28.53	27.17	33.55	31.73	28.93
2000	Speed / rpm	1.2	1.4	1.3	1.5	1.3	1.6	1.6
	Torque / N·m	0.25	0.26	0.29	0.26	0.20	0.26	0.24
	Power / W	51.63	54.77	59.71	54.89	41.29	54.19	50.70
2250	Speed / rpm	1.4	1.5	1.4	2.2	1.4	1.3	1.5
	Torque / N·m	0.27	0.30	0.30	0.30	0.29	0.32	0.34
	Power / W	63.57	69.93	70.58	71.43	67.85	75.83	80.54
2500	Speed / rpm	1.2	1.3	1.3	1.3	1.3	1.1	1.8
	Torque / N·m	0.35	0.41	0.41	0.43	0.45	0.46	0.42
	Power / W	91.35	107.48	108.26	113.68	117.56	119.96	110.24

Table C.6: Second experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.6	499.7	499.8	500.1	499.3	496.9	501.3
	Torque / N·m	1.01	0.79	0.70	0.66	0.59	0.50	0.40
	Power / W	52.95	41.13	36.62	34.68	31.02	25.96	21.16
	T_{VL} / °C	50.1	53.2	57.3	62.4	68.6	77.4	90.4
750	Speed / rpm	751.5	750.5	747.4	746.8	749.4	745.8	748.5
	Torque / N·m	1.31	1.05	0.95	0.89	0.85	0.69	0.52
	Power / W	103.10	82.38	74.30	69.80	66.39	53.76	40.94
	T_{VL} / °C	50.2	53.3	57.3	62.1	68.6	77.3	90.3
1000	Speed / rpm	1002.3	1001.5	999.9	1000.2	997.8	998.8	1001.8
	Torque / N·m	1.42	1.22	1.06	1.03	0.95	0.85	0.65
	Power / W	149.17	127.55	111.47	107.61	99.41	88.83	67.68
	T_{VL} / °C	50.2	53.1	57.3	62.1	68.5	77.0	90.1
1500	Speed / rpm	1500.8	1499.7	1497.4	1500.0	1500.0	1499.8	1498.7
	Torque / N·m	1.48	1.38	1.27	1.22	1.16	1.03	0.80
	Power / W	231.86	216.71	199.24	192.38	181.80	162.28	125.56
	T_{VL} / °C	50.3	53.1	57.3	62.2	68.4	77.2	90.1
2000	Speed / rpm	2001.0	1997.5	1998.4	1996.9	2000.4	2000.1	1999.1
	Torque / N·m	1.74	1.67	1.45	1.40	1.26	1.22	1.14
	Power / W	363.72	349.56	302.55	293.14	264.96	254.89	237.79
	T_{VL} / °C	50.2	53.1	57.2	62.1	68.5	77.3	90.3
2250	Speed / rpm	2250.9	2248.4	2247.1	2248.8	2251.2	2250.3	2250.3
	Torque / N·m	1.89	1.82	1.77	1.70	1.51	1.24	1.13
	Power / W	446.60	429.57	415.89	401.34	356.20	293.27	265.21
	T_{VL} / °C	50.3	53.0	57.2	62.0	68.5	77.3	90.2
2500	Speed / rpm	2497.6	2501.0	2502.4	2499.1	2498.6	2500.8	2498.0
	Torque / N·m	2.02	1.71	1.90	1.92	1.89	1.83	1.57
	Power / W	529.26	446.81	497.22	503.21	495.77	477.97	410.39
	T_{VL} / °C	50.5	53.1	57.4	61.9	68.4	77.2	90.3

Table C.7: Standard deviation of the second experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.4	1.5	1.5	1.0	1.8	1.4	1.7
	Torque / N·m	0.17	0.26	0.26	0.26	0.27	0.27	0.26
	Power / W	8.77	13.56	13.80	13.80	14.11	13.93	13.63
750	Speed / rpm	1.3	1.2	1.5	1.6	1.4	1.8	1.4
	Torque / N·m	0.19	0.28	0.28	0.27	0.25	0.25	0.24
	Power / W	14.57	22.06	22.20	20.90	19.86	19.72	18.58
1000	Speed / rpm	1.2	1.3	1.1	1.0	2.1	1.0	1.2
	Torque / N·m	0.15	0.19	0.24	0.21	0.20	0.21	0.21
	Power / W	15.37	19.95	25.31	21.97	21.03	21.92	21.57
1500	Speed / rpm	1.3	1.0	1.3	1.1	1.0	1.3	1.2
	Torque / N·m	0.21	0.15	0.21	0.14	0.15	0.30	0.23
	Power / W	32.64	24.23	33.41	21.62	22.85	46.46	35.50
2000	Speed / rpm	1.7	1.7	1.8	2.2	1.6	1.4	1.9
	Torque / N·m	0.28	0.29	0.30	0.29	0.28	0.33	0.33
	Power / W	57.77	60.11	62.02	60.34	58.17	69.77	69.05
2250	Speed / rpm	1.4	1.6	1.6	1.5	1.4	1.3	1.5
	Torque / N·m	0.37	0.33	0.35	0.30	0.29	0.28	0.32
	Power / W	86.48	77.65	82.76	70.81	68.98	66.32	74.51
2500	Speed / rpm	1.4	1.7	2.5	1.4	1.3	1.3	1.6
	Torque / N·m	0.53	0.47	0.43	0.47	0.47	0.46	0.45
	Power / W	139.81	124.28	113.76	123.13	122.89	120.62	117.84

Table C.8: Third experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.1	499.8	499.6	499.7	499.9	499.7	501.0
	Torque / N·m	0.83	0.72	0.71	0.65	0.58	0.50	0.39
	Power / W	43.54	37.91	37.32	34.06	30.55	26.26	20.51
	T_{VL} / °C	50.1	53.5	57.4	62.4	68.7	77.4	90.4
750	Speed / rpm	748.4	750.3	747.1	749.5	749.8	746.0	745.8
	Torque / N·m	1.14	0.98	0.96	0.91	0.78	0.70	0.52
	Power / W	88.99	76.95	74.74	71.37	61.62	54.33	40.52
	T_{VL} / °C	50.2	53.2	57.3	62.2	68.5	77.5	90.3
1000	Speed / rpm	1001.8	1003.3	1000.1	999.6	1000.1	995.9	999.0
	Torque / N·m	1.29	1.16	1.09	1.06	1.00	0.86	0.64
	Power / W	135.32	122.08	114.60	110.44	104.36	89.49	67.15
	T_{VL} / °C	50.0	53.0	57.0	62.1	68.5	77.2	90.3
1500	Speed / rpm	1499.3	1504.3	1501.0	1501.3	1497.4	1496.8	1498.5
	Torque / N·m	1.32	1.32	1.29	1.21	1.12	1.00	0.80
	Power / W	206.93	207.55	203.06	189.74	175.58	157.11	124.80
	T_{VL} / °C	50.1	53.0	57.2	62.2	68.4	77.3	90.1
2000	Speed / rpm	2001.1	1999.5	2001.6	2001.2	2000.4	2000.2	1999.2
	Torque / N·m	1.44	1.46	1.37	1.32	1.23	1.14	0.90
	Power / W	301.12	306.27	286.90	276.68	257.65	239.63	189.15
	T_{VL} / °C	49.9	53.0	57.0	62.3	68.5	77.6	90.1
2250	Speed / rpm	2248.0	2252.4	2251.2	2253.2	2250.8	2249.8	2249.9
	Torque / N·m	1.44	1.44	1.40	1.33	1.25	1.16	0.92
	Power / W	339.59	340.64	330.20	314.94	294.40	272.50	217.50
	T_{VL} / °C	49.9	52.9	57.1	62.0	68.4	77.5	89.9
2500	Speed / rpm	2502.4	2500.8	2502.1	2501.9	2497.7	2499.4	2499.9
	Torque / N·m	1.75	1.68	1.57	1.64	1.44	1.37	1.19
	Power / W	458.65	439.95	412.15	428.39	377.61	358.20	311.14
	T_{VL} / °C	50.0	53.0	57.1	62.0	68.3	77.2	89.8

Table C.9: Standard deviation of the third experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.5	1.3	1.4	1.3	1.3	1.4	1.5
	Torque / N·m	0.21	0.25	0.25	0.26	0.25	0.26	0.24
	Power / W	11.18	13.03	13.04	13.45	13.18	13.46	12.83
750	Speed / rpm	1.4	1.6	1.6	1.2	1.1	1.7	1.7
	Torque / N·m	0.24	0.24	0.27	0.27	0.23	0.26	0.23
	Power / W	18.50	18.98	21.11	20.86	18.44	20.17	17.62
1000	Speed / rpm	1.3	1.5	1.2	1.2	1.0	1.7	1.2
	Torque / N·m	0.18	0.18	0.21	0.19	0.17	0.19	0.18
	Power / W	19.05	18.95	21.87	19.89	17.88	19.84	18.82
1500	Speed / rpm	2.0	1.8	1.4	1.4	1.3	1.5	1.3
	Torque / N·m	0.13	0.21	0.20	0.20	0.21	0.20	0.18
	Power / W	20.48	32.39	31.85	31.14	32.70	31.93	28.97
2000	Speed / rpm	1.4	1.3	1.4	1.1	1.3	1.0	1.2
	Torque / N·m	0.27	0.31	0.28	0.27	0.24	0.30	0.24
	Power / W	57.23	65.46	58.75	56.24	51.05	62.65	51.04
2250	Speed / rpm	1.4	1.4	1.2	1.6	1.3	1.4	1.2
	Torque / N·m	0.32	0.31	0.31	0.32	0.30	0.35	0.29
	Power / W	76.06	72.65	72.88	74.37	69.57	82.34	68.41
2500	Speed / rpm	1.6	1.5	1.5	1.7	2.1	1.3	1.5
	Torque / N·m	0.51	0.48	0.47	0.47	0.44	0.42	0.42
	Power / W	132.64	125.49	123.72	122.70	114.96	109.19	109.47

C.2.3 Rolling Bearings Power Loss results - Second Test

Table C.10: First experimental results for the rolling bearings - Second test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	501.2	500.6	497.1	498.5	497.9	500.1	498.5
	Torque / N·m	1.17	0.92	0.90	0.77	0.66	0.63	0.51
	Power / W	61.41	48.45	46.61	40.28	34.39	32.73	26.54
	T_{VL} / °C	43.6	52.0	52.8	58.5	63.3	67.2	75.6
	T_{bath} / °C	50.5	55.6	57.1	62.6	69.9	77.9	94.8
750	Speed / rpm	752.4	748.4	747.8	747.9	750.3	749.8	748.1
	Torque / N·m	1.43	1.16	1.13	0.98	0.89	0.83	0.65
	Power / W	112.59	90.74	88.56	76.95	70.29	64.80	51.00
	T_{VL} / °C	44.9	52.2	53.5	58.1	62.5	66.3	75.0
	T_{bath} / °C	51.8	55.7	60.2	62.8	68.7	77.0	92.0
1000	Speed / rpm	1003.0	1001.9	1000.8	997.3	999.8	998.1	999.3
	Torque / N·m	1.48	1.26	1.19	1.09	1.01	0.90	0.83
	Power / W	154.94	131.78	124.24	113.51	105.75	94.34	86.62
	T_{VL} / °C	46.9	52.9	54.7	58.3	63.0	66.6	75.1
	T_{bath} / °C	51.1	54.3	58.5	62.0	69.0	76.8	90.6
1500	Speed / rpm	1498.8	1497.5	1496.6	1496.9	1498.2	1501.0	1500.2
	Torque / N·m	1.59	1.59	1.57	1.57	1.35	1.32	1.16
	Power / W	249.69	249.79	245.32	246.41	211.29	207.51	181.76
	T_{VL} / °C	50.1	54.8	56.6	60.2	64.0	68.2	77.0
	T_{bath} / °C	51.8	54.5	57.9	64.0	70.2	78.0	89.2
2000	Speed / rpm	2003.8	2001.0	2000.2	2002.5	1998.9	1998.3	1997.6
	Torque / N·m	1.42	1.39	1.48	1.47	1.48	1.26	1.32
	Power / W	298.70	290.55	310.80	307.30	310.62	263.35	276.53
	T_{VL} / °C	54.1	57.4	60.1	63.5	67.3	71.0	80.5
	T_{bath} / °C	52.3	55.5	58.7	64.7	71.2	78.9	90.8
2250	Speed / rpm	2250.0	2253.3	2250.3	2252.0	2251.9	2250.9	2251.0
	Torque / N·m	1.24	1.13	1.47	1.48	1.34	1.40	1.30
	Power / W	291.71	266.62	347.57	348.43	315.58	330.99	306.91
	T_{VL} / °C	56.6	59.4	62.9	66.2	69.7	73.7	83.9
	T_{bath} / °C	51.1	54.0	58.3	62.8	69.8	77.7	91.5
2500	Speed / rpm	2499.8	2500.1	2499.2	2499.0	2498.9	2497.7	2497.8
	Torque / N·m	1.41	1.20	1.52	1.52	1.54	1.49	1.03
	Power / W	369.82	313.45	398.32	396.56	403.36	390.30	270.11
	T_{VL} / °C	59.5	60.7	66.4	69.1	73.1	76.9	86.4
	T_{bath} / °C	50.7	54.4	58.2	63.2	70.0	77.2	91.1

Table C.11: Standard deviation of the first experimental results for the rolling bearings - Second test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.6	1.5	1.5	2.0	1.7	1.5	1.8
	Torque / N·m	0.20	0.24	0.24	0.23	0.23	0.24	0.24
	Power / W	10.30	12.44	12.51	11.80	11.95	12.81	12.73
750	Speed / rpm	1.5	1.5	1.4	1.5	1.5	1.4	2.2
	Torque / N·m	0.21	0.24	0.25	0.21	0.24	0.23	0.23
	Power / W	16.40	18.90	19.59	16.73	18.99	18.12	17.73
1000	Speed / rpm	1.4	1.6	1.1	1.4	1.5	1.9	1.2
	Torque / N·m	0.16	0.18	0.18	0.15	0.16	0.19	0.19
	Power / W	17.30	19.11	18.38	15.70	16.95	19.40	19.46
1500	Speed / rpm	1.2	1.6	1.7	2.0	1.3	1.4	1.2
	Torque / N·m	0.20	0.23	0.19	0.21	0.20	0.20	0.13
	Power / W	30.68	36.58	30.55	32.47	31.25	31.87	20.44
2000	Speed / rpm	1.9	1.4	1.7	1.7	1.6	1.5	1.5
	Torque / N·m	0.27	0.26	0.25	0.32	0.27	0.26	0.26
	Power / W	56.95	53.61	51.65	67.51	57.26	54.49	55.37
2250	Speed / rpm	1.9	1.7	1.2	1.3	1.5	1.3	1.3
	Torque / N·m	0.26	0.34	0.32	0.33	0.32	0.30	0.30
	Power / W	60.87	80.87	76.33	77.31	76.54	71.24	70.85
2500	Speed / rpm	1.1	1.1	1.5	1.4	1.5	1.5	1.5
	Torque / N·m	0.48	0.45	0.47	0.44	0.44	0.43	0.41
	Power / W	125.06	116.98	121.85	116.41	116.01	112.77	106.55

C.2.4 Rolling Bearings Power Loss results - Third Test

Table C.12: First experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.0	500.5	500.1	496.9	499.3	499.6	500.3
	Torque / N·m	1.40	0.86	0.81	0.78	0.75	0.63	0.49
	Power / W	73.30	45.10	42.63	40.82	39.10	33.00	25.87
	T_{VL} / °C	50.0	52.9	57.3	62.0	68.4	77.0	90.2
750	Speed / rpm	752.3	747.9	749.0	750.2	747.0	750.1	745.8
	Torque / N·m	1.57	1.13	1.07	0.98	0.97	0.87	0.63
	Power / W	123.49	88.20	84.09	77.36	76.03	68.30	49.16
	T_{VL} / °C	50.1	52.8	57.5	62.0	68.1	77.2	90.5
1000	Speed / rpm	1003.4	998.8	1000.8	1000.2	997.4	999.5	999.1
	Torque / N·m	1.62	1.28	1.17	1.18	1.12	0.99	0.76
	Power / W	169.77	134.19	122.12	123.21	116.85	103.53	79.64
	T_{VL} / °C	50.4	52.7	57.5	62.1	68.1	77.2	90.4
1500	Speed / rpm	1498.6	1499.8	1499.1	1498.2	1497.8	1497.5	1499.0
	Torque / N·m	1.65	1.35	1.39	1.32	1.27	1.13	0.90
	Power / W	259.06	212.76	217.63	207.78	198.68	176.48	142.00
	T_{VL} / °C	50.6	53.1	57.4	62.0	67.8	76.7	89.8
2000	Speed / rpm	2004.2	1998.9	2000.7	1999.6	1999.0	1998.2	2000.7
	Torque / N·m	1.90	1.72	1.59	1.61	1.59	1.32	1.21
	Power / W	399.04	360.60	332.94	337.03	332.45	275.22	254.50
	T_{VL} / °C	51.5	53.9	57.8	62.5	68.5	76.7	89.1
2250	Speed / rpm	2248.7	2251.1	2250.4	2251.7	2252.3	2251.1	2251.2
	Torque / N·m	1.90	1.65	1.69	1.69	1.59	1.36	1.17
	Power / W	447.57	388.26	397.50	398.01	374.55	320.37	276.05
	T_{VL} / °C	53.0	54.7	58.6	63.2	69.2	76.9	89.5
2500	Speed / rpm	2500.8	2501.6	2503.8	2500.5	2503.0	2503.0	2499.2
	Torque / N·m	1.99	1.68	1.71	1.74	1.69	1.61	1.36
	Power / W	521.17	440.02	448.16	456.33	443.76	423.12	355.33
	T_{VL} / °C	54.4	55.9	59.7	64.0	69.6	77.3	90.4

Table C.13: Standard deviation of the first experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	2.0	1.5	1.6	1.6	1.7	2.1	1.5
	Torque / N·m	0.19	0.23	0.23	0.24	0.25	0.24	0.24
	Power / W	10.21	12.15	12.15	12.26	12.94	12.41	12.43
750	Speed / rpm	1.4	1.5	2.1	1.4	1.4	1.4	1.7
	Torque / N·m	0.20	0.23	0.24	0.22	0.24	0.20	0.22
	Power / W	16.17	18.01	18.60	17.07	18.87	15.68	16.90
1000	Speed / rpm	1.5	1.2	1.4	1.1	1.3	1.5	1.3
	Torque / N·m	0.16	0.17	0.16	0.19	0.18	0.18	0.19
	Power / W	16.90	17.77	16.68	20.09	19.19	19.16	19.77
1500	Speed / rpm	1.4	1.2	1.6	1.4	1.3	1.5	1.3
	Torque / N·m	0.19	0.13	0.26	0.20	0.20	0.19	0.20
	Power / W	30.23	20.41	41.67	30.98	31.57	30.15	32.01
2000	Speed / rpm	2.3	2.1	2.2	1.9	1.7	1.9	1.6
	Torque / N·m	0.31	0.30	0.32	0.28	0.28	0.28	0.27
	Power / W	64.45	63.86	67.31	57.85	58.33	57.93	56.79
2250	Speed / rpm	1.7	1.5	1.4	2.2	1.6	1.4	1.4
	Torque / N·m	0.30	0.31	0.31	0.31	0.32	0.32	0.34
	Power / W	70.96	72.45	73.68	72.13	75.09	74.89	79.27
2500	Speed / rpm	1.5	1.5	1.7	1.5	1.5	1.6	2.1
	Torque / N·m	0.48	0.47	0.48	0.48	0.49	0.49	0.47
	Power / W	126.55	123.25	125.59	125.98	127.23	128.18	122.68

Table C.14: Second experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.8	501.2	499.2	500.3	499.8	496.8	500.3
	Torque / N·m	1.61	0.89	0.82	0.79	0.74	0.66	0.52
	Power / W	84.34	46.85	42.72	41.16	38.91	34.08	27.43
	T_{VL} / °C	49.9	53.1	56.9	62.0	68.3	77.3	90.3
750	Speed / rpm	753.6	748.8	749.8	747.8	747.9	750.4	750.1
	Torque / N·m	1.79	1.17	1.08	1.04	0.96	0.88	0.68
	Power / W	141.04	91.37	85.03	81.22	75.45	69.48	53.03
	T_{VL} / °C	49.8	53.1	56.9	62.0	68.3	77.1	89.9
1000	Speed / rpm	999.0	999.5	999.0	1001.9	998.9	1000.7	999.8
	Torque / N·m	1.81	1.27	1.18	1.18	1.11	0.98	0.81
	Power / W	189.50	133.39	123.62	124.32	115.66	102.57	84.50
	T_{VL} / °C	50.5	53.1	56.8	61.9	68.1	77.1	89.8
1500	Speed / rpm	1496.8	1501.4	1498.8	1500.9	1500.0	1499.7	1498.4
	Torque / N·m	1.62	1.64	1.36	1.32	1.24	1.16	0.94
	Power / W	253.24	257.30	214.24	207.73	194.40	182.95	147.78
	T_{VL} / °C	51.2	53.6	57.2	62.0	68.0	76.5	88.8
2000	Speed / rpm	2003.1	2000.4	2001.7	2004.4	1999.3	2001.6	2001.6
	Torque / N·m	1.96	1.69	1.56	1.55	1.40	1.32	1.22
	Power / W	412.04	353.78	326.65	326.06	292.45	275.95	254.72
	T_{VL} / °C	52.3	54.5	57.8	62.6	68.7	76.5	88.6
2250	Speed / rpm	2253.6	2251.0	2253.1	2255.2	2254.0	2250.6	2252.5
	Torque / N·m	1.92	1.77	1.73	1.69	1.64	1.39	1.16
	Power / W	452.15	416.63	408.73	399.25	386.65	326.67	273.67
	T_{VL} / °C	53.6	55.6	58.7	63.5	69.4	76.9	88.9
2500	Speed / rpm	2500.0	2507.8	2502.9	2501.5	2501.8	2504.9	2502.3
	Torque / N·m	1.72	2.20	1.67	1.61	1.76	1.63	1.49
	Power / W	451.12	577.05	437.48	422.90	461.36	426.33	390.32
	T_{VL} / °C	54.8	57.5	59.8	64.3	70.4	77.5	89.7

Table C.15: Standard deviation of the second experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.8	2.1	2.7	1.6	1.8	2.0	1.7
	Torque / N·m	0.21	0.24	0.24	0.25	0.27	0.26	0.27
	Power / W	11.10	12.75	12.47	13.00	14.21	13.72	14.08
750	Speed / rpm	2.1	2.0	2.5	2.1	2.1	1.8	2.2
	Torque / N·m	0.21	0.22	0.25	0.24	0.27	0.27	0.27
	Power / W	16.94	17.17	19.50	18.53	21.17	20.86	21.22
1000	Speed / rpm	2.1	2.1	2.2	2.3	2.2	2.0	2.3
	Torque / N·m	0.17	0.18	0.19	0.16	0.19	0.20	0.19
	Power / W	17.67	18.37	19.84	16.54	19.65	21.13	19.62
1500	Speed / rpm	2.7	3.3	2.8	2.7	2.8	2.3	2.8
	Torque / N·m	0.20	0.26	0.20	0.20	0.19	0.20	0.19
	Power / W	31.84	41.20	30.59	31.70	29.51	31.33	29.41
2000	Speed / rpm	3.2	3.9	3.8	4.2	3.5	3.8	3.5
	Torque / N·m	0.25	0.29	0.30	0.27	0.29	0.28	0.26
	Power / W	53.43	61.76	62.26	55.52	60.03	59.46	54.98
2250	Speed / rpm	3.4	4.2	4.0	3.7	3.9	3.8	3.8
	Torque / N·m	0.35	0.33	0.31	0.33	0.32	0.31	0.31
	Power / W	83.43	77.58	74.11	78.31	75.72	73.23	73.10
2500	Speed / rpm	4.0	4.0	4.1	4.0	3.9	4.1	3.7
	Torque / N·m	0.44	0.49	0.46	0.43	0.44	0.42	0.40
	Power / W	115.78	128.14	120.65	112.97	115.18	110.64	104.52

Table C.16: Third experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	499.9	500.6	500.4	500.0	500.3	500.4	500.6
	Torque / N·m	1.46	0.87	0.80	0.75	0.72	0.62	0.49
	Power / W	76.59	45.80	41.73	39.48	37.79	32.73	25.79
	T_{VL} / °C	50.1	53.2	57.1	62.2	68.5	77.1	90.2
750	Speed / rpm	752.4	749.0	749.8	749.8	750.1	748.1	746.2
	Torque / N·m	1.70	1.16	1.07	1.02	0.95	0.88	0.65
	Power / W	134.09	90.73	83.65	79.90	74.75	68.73	50.77
	T_{VL} / °C	50.1	53.3	57.1	62.2	68.4	77.0	90.1
1000	Speed / rpm	1000.8	1002.8	1001.9	998.7	998.8	1000.8	1000.1
	Torque / N·m	1.71	1.24	1.20	1.13	1.09	1.00	0.77
	Power / W	179.27	130.55	125.97	118.32	114.04	104.92	80.91
	T_{VL} / °C	50.4	53.5	56.7	62.2	68.5	77.0	89.9
1500	Speed / rpm	1499.4	1498.9	1500.9	1498.1	1498.5	1499.9	1501.4
	Torque / N·m	1.72	1.45	1.35	1.38	1.23	1.13	0.91
	Power / W	270.26	226.91	211.54	216.96	192.74	177.76	143.12
	T_{VL} / °C	50.7	53.7	56.9	62.2	68.1	76.4	89.5
2000	Speed / rpm	1998.7	2003.3	2001.1	2000.2	1999.4	1998.6	2001.1
	Torque / N·m	2.02	1.76	1.64	1.41	1.50	1.32	1.11
	Power / W	422.80	369.08	344.60	295.27	313.71	276.00	233.55
	T_{VL} / °C	51.8	54.7	57.7	62.8	68.6	76.5	89.2
2250	Speed / rpm	2248.0	2249.9	2251.0	2251.7	2250.6	2249.2	2252.7
	Torque / N·m	1.86	1.75	1.68	1.63	1.55	1.30	1.07
	Power / W	438.35	411.55	395.96	384.80	365.19	306.96	252.08
	T_{VL} / °C	53.1	55.8	58.7	63.8	69.6	76.9	89.3
2500	Speed / rpm	2500.4	2500.5	2497.2	2496.2	2499.4	2500.9	2500.3
	Torque / N·m	1.80	1.66	1.63	1.64	1.56	1.45	1.46
	Power / W	471.90	434.75	425.37	427.88	408.94	380.39	381.15
	T_{VL} / °C	54.4	57.0	59.9	64.5	70.4	77.4	90.0

Table C.17: Standard deviation of the third experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.3	1.8	1.8	2.0	1.9	2.0	1.8
	Torque / N·m	0.19	0.24	0.24	0.25	0.26	0.27	0.24
	Power / W	9.74	12.77	12.79	13.10	13.80	13.92	12.67
750	Speed / rpm	1.4	2.1	2.2	1.8	1.9	2.4	2.1
	Torque / N·m	0.21	0.24	0.25	0.25	0.26	0.25	0.22
	Power / W	16.31	19.04	19.89	20.00	20.59	19.92	17.06
1000	Speed / rpm	1.2	2.2	2.3	2.0	2.4	1.8	2.0
	Torque / N·m	0.16	0.18	0.18	0.18	0.20	0.22	0.15
	Power / W	17.21	18.90	18.71	19.12	20.57	22.98	16.10
1500	Speed / rpm	1.3	3.2	2.6	3.2	2.9	2.6	2.5
	Torque / N·m	0.22	0.22	0.20	0.22	0.20	0.20	0.20
	Power / W	34.94	34.44	31.83	35.11	30.66	31.95	31.02
2000	Speed / rpm	1.9	3.9	3.9	3.6	3.8	3.2	3.4
	Torque / N·m	0.27	0.30	0.29	0.30	0.29	0.27	0.30
	Power / W	55.53	62.74	60.40	62.14	61.44	57.30	61.98
2250	Speed / rpm	1.7	4.0	3.6	3.7	3.6	3.3	3.7
	Torque / N·m	0.34	0.33	0.33	0.34	0.32	0.31	0.33
	Power / W	79.20	77.54	78.75	79.65	74.73	72.07	77.27
2500	Speed / rpm	1.4	3.6	3.8	4.1	4.1	4.0	4.1
	Torque / N·m	0.55	0.48	0.46	0.45	0.41	0.47	0.43
	Power / W	144.68	126.11	119.83	117.27	106.21	122.69	112.43

C.2.5 Pinion and Rolling Bearings Power Loss results - Second test

Table C.18: First experimental results for the pinion and rolling bearings - Second test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	501.6	497.4	500.0	500.3	500.5	501.3	502.2
	Torque / N·m	1.08	0.95	0.83	0.77	0.64	0.55	0.42
	Power / W	56.86	49.29	43.65	40.43	33.40	28.93	22.32
	T_{VL} / °C	50.1	53.1	57.2	61.4	68.4	76.1	78.4
	T_{bath} / °C	50.0	52.9	57.6	62.3	68.6	77.4	90.9
750	Speed / rpm	749.9	751.8	745.5	749.5	747.3	744.9	747.4
	Torque / N·m	1.31	1.19	1.08	1.01	0.84	0.72	0.57
	Power / W	103.19	93.73	84.30	79.26	65.48	56.18	44.90
	T_{VL} / °C	48.4	51.6	55.9	60.7	67.9	76.2	83.0
	T_{bath} / °C	50.4	53.5	57.2	62.4	68.5	77.4	90.1
1000	Speed / rpm	1001.4	999.0	1001.2	1001.9	1000.4	1001.8	1001.2
	Torque / N·m	1.46	1.33	1.17	1.15	0.98	0.88	0.69
	Power / W	152.78	138.97	122.55	120.95	102.60	92.38	72.62
	T_{VL} / °C	50.1	53.1	56.4	60.1	65.3	72.8	83.4
	T_{bath} / °C	51.4	53.4	56.8	62.2	67.6	78.3	90.4
1500	Speed / rpm	1499.9	1501.5	1500.0	1500.3	1496.8	1503.9	1499.6
	Torque / N·m	1.58	1.48	1.38	1.31	1.18	1.03	0.86
	Power / W	248.29	232.56	217.52	205.31	185.25	161.69	134.56
	T_{VL} / °C	53.9	56.4	59.2	62.4	66.8	74.5	85.4
	T_{bath} / °C	52.9	54.2	57.7	63.1	68.2	79.6	91.7
2000	Speed / rpm	1999.6	1999.8	1998.4	2001.2	1998.0	2002.7	2004.8
	Torque / N·m	1.58	1.51	1.44	1.37	1.27	1.13	0.97
	Power / W	330.11	315.77	301.13	286.77	265.95	236.87	202.99
	T_{VL} / °C	59.3	60.2	62.3	65.7	70.1	76.8	86.5
	T_{bath} / °C	54.8	54.3	57.3	61.9	68.6	78.7	91.4
2250	Speed / rpm	2250.5	2247.8	2252.4	2252.3	2250.5	2251.5	2249.5
	Torque / N·m	1.53	1.48	1.43	1.37	1.26	1.15	1.00
	Power / W	360.27	348.20	337.95	322.71	296.52	271.77	235.09
	T_{VL} / °C	63.6	63.8	65.6	68.6	73.0	78.7	88.0
	T_{bath} / °C	56.9	55.7	58.4	62.3	68.0	79.0	91.2
2500	Speed / rpm	2508.8	2499.3	2502.2	2499.9	2495.9	2501.6	2502.9
	Torque / N·m	1.50	1.46	1.43	1.36	1.25	1.18	1.04
	Power / W	394.30	380.91	373.68	356.90	326.13	307.92	272.03
	T_{VL} / °C	67.5	67.7	69.1	71.7	75.6	81.5	89.3
	T_{bath} / °C	58.9	58.4	60.2	63.6	68.6	81.6	91.2

Table C.19: Standard deviation of the first experimental results for the pinion and rolling bearings - Second test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	2.1	2.2	1.9	2.3	2.1	2.0	2.0
	Torque / N·m	0.19	0.23	0.24	0.26	0.26	0.20	0.25
	Power / W	10.03	11.95	12.79	13.57	13.72	10.42	13.11
750	Speed / rpm	2.1	2.0	2.3	2.8	2.1	2.2	2.5
	Torque / N·m	0.19	0.25	0.25	0.25	0.28	0.19	0.23
	Power / W	15.26	19.42	19.87	19.92	21.68	14.88	18.17
1000	Speed / rpm	2.4	2.3	2.4	2.2	2.1	2.7	2.7
	Torque / N·m	0.16	0.20	0.17	0.16	0.19	0.14	0.19
	Power / W	17.07	20.77	18.15	17.15	20.17	15.03	19.80
1500	Speed / rpm	2.4	2.3	2.5	2.6	3.2	2.8	2.5
	Torque / N·m	0.21	0.13	0.20	0.20	0.21	0.19	0.21
	Power / W	32.31	21.17	30.99	31.80	32.60	30.35	32.30
2000	Speed / rpm	3.3	2.7	3.1	3.2	3.1	2.9	3.8
	Torque / N·m	0.26	0.27	0.28	0.28	0.28	0.28	0.30
	Power / W	53.92	56.43	59.52	58.59	58.42	58.54	63.07
2250	Speed / rpm	3.4	3.1	2.7	2.9	3.0	3.5	3.5
	Torque / N·m	0.33	0.32	0.34	0.32	0.30	0.33	0.30
	Power / W	77.27	74.67	79.29	76.49	70.12	77.67	70.64
2500	Speed / rpm	3.6	3.3	3.3	3.2	3.7	3.4	3.5
	Torque / N·m	0.47	0.45	0.43	0.43	0.41	0.42	0.41
	Power / W	122.47	117.91	112.89	112.82	106.56	110.18	107.00

C.2.6 Rolling Bearings Power Loss results - Forth Test

Table C.20: Forth experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	497,5	498,1	500,3	497,0	499,9	500,3	501,2
	Torque / N·m	1,07	0,93	0,82	0,74	0,58	0,48	0,37
	Power / W	55,79	48,31	42,82	38,46	30,28	25,39	19,61
	T_{VL} / °C	50,1	53,4	57,2	62,1	68,1	77,4	90,0
	Q / $l\ min^{-1}$	0.60	0.64	0.88	0.96	1.03	0.99	0.34
750	Speed / rpm	752,6	747,7	750,7	749,8	745,9	749,0	748,5
	Torque / N·m	1,26	1,14	1,03	0,90	0,78	0,68	0,53
	Power / W	99,25	89,18	80,73	70,71	60,65	53,19	41,65
	T_{VL} / °C	48,5	51,8	55,2	61,1	66,4	74,9	88,2
	Q / $l\ min^{-1}$	0.31	0.31	0.35	0.30	0.42	0.40	0.37
1000	Speed / rpm	1003,9	1002,1	998,8	1000,3	998,9	998,9	998,4
	Torque / N·m	1,38	1,24	1,18	1,07	0,94	0,81	0,63
	Power / W	144,91	129,89	123,64	111,78	98,40	84,62	65,78
	T_{VL} / °C	49,4	52,7	56,1	60,9	66,1	76,1	89,7
	Q / $l\ min^{-1}$	0.38	0.40	0.35	0.35	0.39	0.44	0.51
1500	Speed / rpm	1497,2	1500,9	1498,1	1500,0	1499,6	1499,2	1496,2
	Torque / N·m	1,47	1,39	1,32	1,31	1,08	0,96	0,78
	Power / W	230,82	219,25	207,14	205,95	169,69	151,49	122,68
	T_{VL} / °C	50,4	53,6	57,0	62,9	67,7	77,3	91,8
	Q / $l\ min^{-1}$	0.35	0.44	0.46	0.47	0.55	0.56	0.51
2000	Speed / rpm	2002,3	2001,7	2000,7	1997,0	1998,7	1999,7	1998,8
	Torque / N·m	321,66	310,35	282,75	276,37	267,13	233,80	203,97
	Power / W	321,66	310,35	282,75	276,37	267,13	233,80	203,97
	T_{VL} / °C	51,8	55,7	59,6	64,6	69,0	77,7	92,5
	Q / $l\ min^{-1}$	0.35	0.44	0.48	0.48	0.55	0.58	0.76
2250	Speed / rpm	2252,5	2253,7	2248,8	2250,5	2246,5	2248,9	2248,8
	Torque / N·m	1,50	1,43	1,39	1,29	1,27	1,12	0,92
	Power / W	352,76	338,17	327,83	303,70	299,12	264,90	216,28
	T_{VL} / °C	53,9	57,5	61,0	65,7	69,4	78,3	93,4
	Q / $l\ min^{-1}$	0.42	0.44	0.46	0.51	0.61	0.72	0.67
2500	Speed / rpm	2501,9	2500,5	2503,0	2499,0	2498,4	2498,8	2495,9
	Torque / N·m	1,51	1,48	1,42	1,34	1,29	1,16	0,99
	Power / W	394,45	386,68	372,32	350,00	336,87	304,49	259,14
	T_{VL} / °C	53,7	57,8	61,2	66,3	70,2	79,6	93,6
	Q / $l\ min^{-1}$	0.44	0.50	0.52	0.54	0.57	0.69	0.70

Table C.21: Standard deviation of the forth experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.7	3.1	2.1	1.5	1.5	1.6	1.5
	Torque / N·m	0.19	0.25	0.28	0.24	0.29	0.26	0.25
	Power / W	9.98	13.22	14.73	12.24	15.01	13.56	13.34
750	Speed / rpm	1.9	2.3	2.2	1.4	1.6	1.4	1.3
	Torque / N·m	0.20	0.27	0.30	0.22	0.28	0.25	0.23
	Power / W	15.41	21.48	23.46	17.66	21.73	19.32	18.20
1000	Speed / rpm	2.2	3.0	2.6	1.1	1.4	1.2	1.3
	Torque / N·m	0.16	0.20	0.23	0.18	0.22	0.18	0.17
	Power / W	17.22	21.46	24.45	18.66	22.80	18.89	17.50
1500	Speed / rpm	2.9	3.0	3.3	1.0	1.1	1.4	1.6
	Torque / N·m	0.20	0.20	0.19	0.32	0.17	0.18	0.19
	Power / W	30.75	30.93	30.53	49.63	27.06	28.09	29.07
2000	Speed / rpm	3.7	3.4	3.9	1.7	1.5	0.9	1.3
	Torque / N·m	0.26	0.28	0.30	0.26	0.27	0.28	0.24
	Power / W	55.45	57.64	63.88	54.80	56.19	58.85	51.04
2250	Speed / rpm	3.9	3.6	3.9	1.0	1.9	1.3	1.3
	Torque / N·m	0.32	0.29	0.28	0.27	0.39	0.29	0.29
	Power / W	76.38	68.20	66.13	64.51	92.71	69.27	69.20
2500	Speed / rpm	4.1	4.0	4.3	1.3	1.3	1.9	1.7
	Torque / N·m	0.43	0.38	0.42	0.37	0.40	0.35	0.38
	Power / W	112.95	100.42	109.38	98.00	103.59	90.99	99.82

Table C.22: Forth experimental results for the rolling bearings - Second test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.5	500.1	499.2	496.4	499.7	500.7	501.2
	Torque / N·m	1.07	0.93	0.82	0.72	0.60	0.48	0.37
	Power / W	55.92	48.49	42.69	37.18	31.63	24.96	19.44
	T_{VL} / °C	49.5	52.9	57.2	62.0	68.4	77.1	90.1
750	Speed / rpm	751.1	750.4	747.0	749.4	749.1	748.7	751.7
	Torque / N·m	1.25	1.14	1.04	0.95	0.81	0.67	0.52
	Power / W	98.14	89.89	81.48	74.62	63.91	52.50	40.62
	T_{VL} / °C	49.1	51.0	55.7	59.9	68.0	76.4	89.1
1000	Speed / rpm	1002.1	997.8	997.1	999.5	998.9	998.7	998.3
	Torque / N·m	1.41	1.31	1.21	1.10	0.97	0.81	0.62
	Power / W	147.58	136.57	126.26	115.57	101.88	85.02	65.29
	T_{VL} / °C	49.8	51.5	55.7	60.3	68.1	75.8	89.2
1500	Speed / rpm	1501.8	1499.3	1498.5	1494.6	1499.3	1499.3	1498.2
	Torque / N·m	1.61	1.49	1.42	1.34	1.16	1.03	0.83
	Power / W	253.67	233.25	222.91	209.31	182.64	161.79	129.95
	T_{VL} / °C	50.4	52.3	56.9	61.3	68.3	76.5	89.3
2000	Speed / rpm	2001.5	1999.5	1995.0	1996.3	1999.7	1996.4	1998.8
	Torque / N·m	1.71	1.66	1.54	1.36	1.32	1.18	0.98
	Power / W	357.86	347.75	321.66	285.17	276.38	246.79	205.25
	T_{VL} / °C	51.6	52.9	57.8	62.7	68.7	76.8	89.4
2250	Speed / rpm	2251.9	2249.4	2247.7	2249.2	2248.7	2249.6	2249.4
	Torque / N·m	1.67	1.60	1.52	1.44	1.36	1.22	1.00
	Power / W	393.35	376.99	357.07	338.25	319.25	286.42	236.49
	T_{VL} / °C	52.7	54.2	59.3	63.7	69.3	77.4	89.5
2500	Speed / rpm	2501.9	2499.0	2498.1	2496.3	2498.9	2498.5	2498.0
	Torque / N·m	1.65	1.59	1.54	1.44	1.36	1.26	1.09
	Power / W	432.66	415.85	403.16	376.82	355.20	329.54	284.66
	T_{VL} / °C	52.8	54.7	59.4	64.0	69.6	78.1	90.4

Table C.23: Standard deviation of the forth experimental results for the rolling bearings - Second test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.6	1.4	1.5	1.6	1.6	1.4	1.6
	Torque / N·m	0.20	0.26	0.28	0.27	0.28	0.27	0.28
	Power / W	10.58	13.57	14.72	14.14	14.62	14.31	14.57
750	Speed / rpm	1.3	1.4	1.4	1.6	1.3	1.4	1.4
	Torque / N·m	0.20	0.30	0.30	0.31	0.30	0.27	0.26
	Power / W	15.52	23.54	23.71	24.50	23.76	21.09	20.11
1000	Speed / rpm	1.2	1.4	1.4	1.1	1.3	1.2	1.4
	Torque / N·m	0.15	0.21	0.22	0.20	0.23	0.23	0.22
	Power / W	16.10	22.41	23.05	21.01	23.91	24.01	23.08
1500	Speed / rpm	1.3	1.3	1.3	1.7	1.3	1.3	1.2
	Torque / N·m	0.20	0.19	0.20	0.21	0.21	0.21	0.22
	Power / W	31.36	29.09	32.05	33.05	33.24	33.25	33.76
2000	Speed / rpm	1.2	1.2	1.6	1.5	1.1	1.8	1.5
	Torque / N·m	0.27	0.34	0.28	0.27	0.25	0.31	0.31
	Power / W	55.89	70.81	57.80	55.99	52.32	65.27	65.07
2250	Speed / rpm	1.6	1.2	1.5	1.4	1.5	1.2	1.2
	Torque / N·m	0.34	0.30	0.38	0.33	0.34	0.38	0.41
	Power / W	79.98	70.90	89.58	77.51	80.59	89.43	96.38
2500	Speed / rpm	1.6	1.4	1.4	1.7	1.6	1.3	2.1
	Torque / N·m	0.49	0.42	0.40	0.39	0.38	0.39	0.38
	Power / W	127.16	110.80	103.50	101.03	98.85	102.12	99.28

Table C.24: Forth experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.1	499.6	499.0	499.8	499.7	500.5	498.3
	Torque / N·m	1.03	0.92	0.83	0.75	0.60	0.46	0.33
	Power / W	54.12	48.33	43.11	39.47	31.43	24.26	17.14
	T_{VL} / °C	50.1	53.5	57.2	62.2	68.3	77.1	90.0
	Q / $l\ min^{-1}$	0.90	0.92	0.91	1.02	1.04	0.94	0.91
750	Speed / rpm	748.7	746.7	748.2	750.1	746.2	749.0	747.9
	Torque / N·m	1.23	1.13	1.04	0.97	0.81	0.67	0.49
	Power / W	96.11	88.14	81.25	76.40	62.98	52.81	38.71
	T_{VL} / °C	49.2	51.8	54.9	60.0	67.6	74.5	87.3
	Q / $l\ min^{-1}$	0.47	0.30	0.32	0.30	0.45	0.38	0.39
1000	Speed / rpm	1002.1	997.2	999.4	1000.6	1002.8	998.6	998.2
	Torque / N·m	1.35	1.26	1.17	1.07	0.96	0.83	0.64
	Power / W	142.03	131.37	122.71	112.33	100.88	86.65	66.78
	T_{VL} / °C	49.5	51.9	55.7	60.3	67.4	74.0	87.7
	Q / $l\ min^{-1}$	0.42	0.36	0.36	0.34	0.44	0.38	0.46
1500	Speed / rpm	1503.7	1494.5	1496.7	1495.8	1497.0	1495.7	1498.2
	Torque / N·m	1.50	1.39	1.33	1.23	1.12	0.99	0.79
	Power / W	235.94	217.26	208.86	192.15	175.61	155.20	123.28
	T_{VL} / °C	50.2	53.8	56.9	62.1	68.0	76.6	89.5
	Q / $l\ min^{-1}$	0.42	0.37	0.45	0.40	0.46	0.50	0.56
2000	Speed / rpm	1997.1	1997.4	1996.7	2001.2	1996.2	1999.1	1998.1
	Torque / N·m	1.53	1.43	1.40	1.32	1.24	1.12	0.96
	Power / W	320.71	299.49	292.90	276.79	258.17	234.19	200.81
	T_{VL} / °C	52.5	55.0	58.4	63.4	69.2	76.8	90.0
	Q / $l\ min^{-1}$	0.53	0.44	0.43	0.47	0.49	0.54	0.61
2250	Speed / rpm	2248.8	2253.6	2248.8	2251.2	2250.0	2248.4	2248.6
	Torque / N·m	1.52	1.42	1.37	1.34	1.09	1.14	0.94
	Power / W	357.07	335.80	322.53	315.31	257.51	267.37	221.98
	T_{VL} / °C	54.0	56.9	60.2	64.6	69.7	77.6	90.3
	Q / $l\ min^{-1}$	0.48	0.42	0.47	0.49	0.54	0.63	0.67
2500	Speed / rpm	2496.3	2502.3	2497.7	2500.2	2496.2	2498.6	2495.8
	Torque / N·m	1.51	1.48	1.39	1.41	1.28	1.16	1.00
	Power / W	393.93	386.60	364.65	368.38	335.13	303.48	261.39
	T_{VL} / °C	54.4	57.3	60.4	65.3	70.2	78.7	90.8
	Q / $l\ min^{-1}$	0.56	0.44	0.48	0.53	0.57	0.64	0.68

Table C.25: Standard deviation of the forth experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.7	1.9	1.6	1.5	1.6	1.4	1.6
	Torque / N·m	0.22	0.24	0.25	0.21	0.26	0.27	0.25
	Power / W	11.28	12.78	13.15	11.00	13.68	14.30	13.28
750	Speed / rpm	1.4	1.7	1.8	1.1	1.7	1.3	1.4
	Torque / N·m	0.21	0.26	0.27	0.23	0.26	0.28	0.27
	Power / W	16.81	20.55	20.87	18.41	20.45	78.1	21.18
1000	Speed / rpm	1.7	1.9	1.6	1.5	1.6	1.4	1.6
	Torque / N·m	0.17	0.18	0.19	0.18	0.19	0.22	0.22
	Power / W	17.77	18.87	19.60	18.74	20.08	23.39	22.69
1500	Speed / rpm	1.6	1.7	1.5	1.9	1.4	1.7	1.3
	Torque / N·m	0.19	0.19	0.19	0.20	0.20	0.23	0.22
	Power / W	30.40	30.27	29.95	31.38	30.84	79.1	34.49
2000	Speed / rpm	1.6	1.3	1.5	1.5	1.7	1.2	1.5
	Torque / N·m	0.27	0.27	0.28	0.27	0.27	0.34	0.33
	Power / W	56.70	56.40	58.03	55.84	55.51	71.99	69.60
2250	Speed / rpm	1.3	1.6	1.1	1.1	0.9	1.3	1.4
	Torque / N·m	0.32	0.31	0.30	0.33	0.49	0.29	0.34
	Power / W	74.43	72.57	71.52	77.90	115.70	80.1	79.06
2500	Speed / rpm	2.4	2.3	2.3	1.3	1.8	1.5	1.7
	Torque / N·m	0.42	0.44	0.43	0.44	0.40	0.38	0.37
	Power / W	109.09	114.44	113.24	115.55	105.40	100.12	95.89

C.2.7 Rolling Bearings Power Loss results - Fifth Test

Table C.26: Fifth experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	500.3	499.6	499.2	499.5	499.5	500.2	501.5
	Torque / N·m	1.00	0.77	0.75	0.66	0.60	0.54	0.34
	Power / W	52.51	40.19	39.12	34.39	31.37	28.33	17.98
	T_{VL} / °C	50.1	53.1	57.4	61.9	68.5	77.2	89.8
	Q / $l\ min^{-1}$	0.34	0.32	0.34	0.37	0.42	0.44	0.52
750	Speed / rpm	748.6	750.1	744.0	749.8	746.1	749.9	748.8
	Torque / N·m	1.26	1.07	0.99	0.91	0.80	0.71	0.50
	Power / W	98.54	84.36	77.22	71.32	62.57	55.87	39.25
	T_{VL} / °C	49.6	53.0	55.7	62.0	68.1	77.4	88.1
	Q / $l\ min^{-1}$	0.34	0.32	0.34	0.37	0.42	0.44	0.52
1000	Speed / rpm	1000.3	997.7	999.6	998.2	999.3	1000.2	998.7
	Torque / N·m	1.40	1.21	1.16	1.05	0.96	0.86	0.63
	Power / W	147.16	126.42	121.65	110.19	100.61	89.62	65.53
	T_{VL} / °C	50.3	53.6	56.0	62.1	68.1	77.3	88.6
	Q / $l\ min^{-1}$	0.34	0.32	0.34	0.37	0.42	0.44	0.52
1500	Speed / rpm	1501.6	1498.3	1498.0	1497.1	1499.7	1497.8	1499.1
	Torque / N·m	1.57	1.35	1.35	1.24	1.04	1.02	0.79
	Power / W	247.03	211.85	212.33	194.69	164.11	159.42	124.41
	T_{VL} / °C	51.2	54.5	57.5	63.0	68.4	77.7	89.0
	Q / $l\ min^{-1}$	0.34	0.32	0.34	0.37	0.42	0.44	0.52
2000	Speed / rpm	2001.6	2005.2	2000.8	2000.2	1999.9	2001.3	2000.1
	Torque / N·m	1.66	1.42	1.43	1.28	1.24	1.13	0.89
	Power / W	348.05	298.40	299.11	268.26	259.46	237.60	187.36
	T_{VL} / °C	52.0	55.5	58.7	63.6	69.7	78.8	88.9
	Q / $l\ min^{-1}$	0.34	0.32	0.34	0.37	0.42	0.44	0.52
2250	Speed / rpm	2255.0	2249.0	2250.6	2250.2	2250.1	2251.4	2250.1
	Torque / N·m	1.55	1.31	1.40	1.26	1.24	1.13	0.90
	Power / W	366.74	307.59	329.10	297.84	292.45	266.88	211.51
	T_{VL} / °C	53.2	56.8	59.8	64.7	70.3	79.5	89.2
	Q / $l\ min^{-1}$	0.34	0.32	0.34	0.37	0.42	0.44	0.52
2500	Speed / rpm	2501.2	2500.9	2497.4	2499.7	2496.1	2500.8	2496.7
	Torque / N·m	1.50	1.30	1.38	1.14	1.14	1.05	0.90
	Power / W	393.98	339.18	359.60	299.56	297.86	275.62	234.79
	T_{VL} / °C	54.0	56.8	59.9	64.9	71.0	80.0	89.3
	Q / $l\ min^{-1}$	0.34	0.32	0.34	0.37	0.42	0.44	0.52

Table C.27: Standard deviation of the fifth experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.5	1.6	1.6	1.5	1.5	1.4	1.3
	Torque / N·m	0.22	0.25	0.26	0.26	0.25	0.22	0.25
	Power / W	11.56	13.24	13.62	13.49	13.28	11.50	12.96
750	Speed / rpm	1.3	1.3	1.6	1.0	1.7	1.1	1.4
	Torque / N·m	0.24	0.28	0.27	0.28	0.26	0.23	0.23
	Power / W	18.63	21.93	21.10	21.90	20.18	17.81	18.31
1000	Speed / rpm	1.7	1.3	1.2	1.9	1.2	1.2	1.9
	Torque / N·m	0.18	0.20	0.20	0.21	0.20	0.17	0.20
	Power / W	18.63	20.83	20.98	21.98	20.89	18.09	20.71
1500	Speed / rpm	1.3	1.4	1.4	1.3	1.3	1.3	1.2
	Torque / N·m	0.20	0.19	0.19	0.21	0.14	0.19	0.21
	Power / W	31.61	30.20	29.14	32.82	22.62	30.14	32.48
2000	Speed / rpm	1.3	1.8	1.2	1.2	1.3	1.4	0.9
	Torque / N·m	0.26	0.27	0.25	0.24	0.26	0.26	0.17
	Power / W	54.97	57.16	53.04	51.05	55.30	53.97	34.59
2250	Speed / rpm	1.6	1.2	1.3	1.1	1.0	1.6	1.3
	Torque / N·m	0.33	0.30	0.34	0.29	0.36	0.32	0.29
	Power / W	78.97	71.77	79.51	68.85	83.93	74.96	68.95
2500	Speed / rpm	1.4	1.4	1.4	1.4	1.8	1.3	1.8
	Torque / N·m	0.49	0.44	0.44	0.40	0.43	0.42	0.39
	Power / W	128.71	116.01	115.91	105.84	113.02	110.33	101.76

Table C.28: Fifth experimental results for the rolling bearings - Second test at 62.2 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$		
		0.3	0.4	0.5
500	Speed / rpm	499.6	500.1	499.9
	Torque / N·m	0.63	0.66	0.73
	Power / W	32.79	34.55	38.21
	T_{VL} / °C	62.3	62.3	62.4
750	Speed / rpm	749.9	749.8	749.2
	Torque / N·m	0.83	0.93	0.96
	Power / W	64.93	73.08	75.17
	T_{VL} / °C	62.2	61.6	62.6
1000	Speed / rpm	999.9	1000.1	1000.6
	Torque / N·m	1.04	1.05	1.08
	Power / W	108.80	109.52	112.89
	T_{VL} / °C	62.8	61.7	62.4
1500	Speed / rpm	1498.8	1500.4	1502.4
	Torque / N·m	1.14	1.26	1.28
	Power / W	178.94	197.68	201.71
	T_{VL} / °C	63.3	62.7	62.7
2000	Speed / rpm	2002.3	2001.4	2002.8
	Torque / N·m	1.24	1.36	1.39
	Power / W	260.45	284.58	290.66
	T_{VL} / °C	63.8	63.4	63.8
2250	Speed / rpm	2252.5	2250.6	2250.0
	Torque / N·m	1.21	1.33	1.37
	Power / W	284.97	313.95	322.99
	T_{VL} / °C	63.9	64.4	64.5
2500	Speed / rpm	2496.8	2497.4	2499.3
	Torque / N·m	1.17	1.32	1.38
	Power / W	306.69	344.19	361.47
	T_{VL} / °C	64.2	64.9	65.0

Table C.29: Standard deviation of the fifth experimental results for the rolling bearings - Second test at 62.2 °C.

Speed rpm	Variable	Oil Flow Rate / $l\ min^{-1}$		
		0.3	0.4	0.5
500	Speed / rpm	1.4	1.6	1.6
	Torque / N·m	0.27	0.25	0.22
	Power / W	13.93	12.98	11.46
750	Speed / rpm	1.4	1.7	1.8
	Torque / N·m	0.27	0.26	0.22
	Power / W	21.02	20.42	17.06
1000	Speed / rpm	1.1	1.3	1.4
	Torque / N·m	0.21	0.20	0.17
	Power / W	21.49	20.57	18.17
1500	Speed / rpm	1.7	1.1	1.4
	Torque / N·m	0.19	0.19	0.19
	Power / W	30.13	29.19	30.11
2000	Speed / rpm	2.2	1.2	1.5
	Torque / N·m	0.28	0.29	0.27
	Power / W	58.66	59.97	55.84
2250	Speed / rpm	1.5	1.3	1.1
	Torque / N·m	0.42	0.32	0.17
	Power / W	100.20	74.44	39.54
2500	Speed / rpm	1.6	1.5	1.3
	Torque / N·m	0.38	0.43	0.47
	Power / W	100.12	112.69	122.65

Table C.30: Fifth experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C 62.2	77.1	77.1
		Oil Flow Rate / $l\ min^{-1}$ 0.2	0.2	0.3
500	Speed / rpm	499.8	499.8	500.6
	Torque / N·m	0.73	0.52	0.47
	Power / W	38.38	27.10	24.46
	T_{VL} / °C	62.3	77.0	77.0
750	Speed / rpm	753.1	753.0	749.7
	Torque / N·m	0.97	0.72	0.65
	Power / W	76.15	56.84	50.65
	T_{VL} / °C	60.9	75.2	76.6
1000	Speed / rpm	1003.2	999.1	999.0
	Torque / N·m	1.09	0.84	0.81
	Power / W	114.07	88.17	84.22
	T_{VL} / °C	61.1	73.7	77.1
1500	Speed / rpm	1498.4	1500.1	1498.7
	Torque / N·m	1.19	1.06	0.93
	Power / W	186.96	166.48	145.21
	T_{VL} / °C	62.8	73.5	77.0
2000	Speed / rpm	1999.1	2000.8	2000.5
	Torque / N·m	1.29	1.13	1.04
	Power / W	270.74	235.94	216.83
	T_{VL} / °C	63.8	74.7	77.0
2250	Speed / rpm	2252.2	2251.3	2250.0
	Torque / N·m	1.31	1.23	1.14
	Power / W	308.80	289.55	267.62
	T_{VL} / °C	65.5	77.1	77.6
2500	Speed / rpm	2502.8	2502.7	2500.3
	Torque / N·m	1.44	1.17	1.15
	Power / W	377.44	305.83	302.13
	T_{VL} / °C	67.6	79.4	79.0

Table C.31: Standard deviation of the fifth experimental results for the rolling bearings - Third test.

Speed rpm	Variable	Temperature / °C 62.2	77.1	77.1
		Oil Flow Rate / $l\ min^{-1}$ 0.2	0.2	0.3
500	Speed / rpm	1.4	1.5	1.6
	Torque / N·m	0.22	0.24	0.24
	Power / W	11.44	12.42	12.64
750	Speed / rpm	1.6	1.5	2.0
	Torque / N·m	0.24	0.23	0.24
	Power / W	18.93	18.39	19.00
1000	Speed / rpm	1.5	1.4	1.2
	Torque / N·m	0.17	0.18	0.19
	Power / W	18.38	18.60	20.11
1500	Speed / rpm	1.2	1.2	1.4
	Torque / N·m	0.20	0.19	0.18
	Power / W	30.73	60.50	28.90
2000	Speed / rpm	1.3	1.2	1.3
	Torque / N·m	0.25	0.25	0.28
	Power / W	52.82	52.52	59.12
2250	Speed / rpm	1.3	1.4	1.4
	Torque / N·m	0.33	0.33	0.23
	Power / W	78.17	78.15	54.83
2500	Speed / rpm	1.8	1.7	1.0
	Torque / N·m	0.47	0.42	0.45
	Power / W	123.71	109.21	117.86

C.2.8 Rolling Bearings Power Loss results - Sixth Test

Table C.32: Sixth experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	499.8	499.8	499.6	499.2	499.8	499.5	497.8
	Torque / N·m	1.00	0.88	0.78	0.71	0.62	0.54	0.44
	Power / W	52.13	46.11	40.97	37.30	32.70	28.19	22.90
	T_{VL} / °C	50.0	53.4	57.0	62.2	68.6	76.9	89.9
750	Speed / rpm	750.8	750.3	749.3	749.7	746.7	749.1	746.2
	Torque / N·m	1.25	1.17	1.04	0.98	0.85	0.73	0.60
	Power / W	98.09	92.14	81.35	76.83	66.49	57.57	46.59
	T_{VL} / °C	49.2	53.2	56.8	62.1	68.1	76.5	86.7
1000	Speed / rpm	1001.7	1001.3	997.2	1000.1	999.8	998.3	999.2
	Torque / N·m	1.40	1.30	1.20	1.11	1.03	0.87	0.72
	Power / W	147.05	136.20	124.83	115.86	107.72	91.02	75.48
	T_{VL} / °C	49.6	53.6	57.4	62.7	68.0	77.0	89.0
1500	Speed / rpm	1499.9	1499.1	1495.6	1497.6	1500.0	1499.2	1497.5
	Torque / N·m	1.63	1.45	1.29	1.21	1.23	1.01	0.85
	Power / W	256.63	227.28	201.68	189.33	193.20	157.98	132.83
	T_{VL} / °C	50.3	54.7	58.3	63.4	68.9	77.5	88.3
2000	Speed / rpm	2003.1	2001.9	1996.9	2000.6	1997.0	2003.1	2002.3
	Torque / N·m	1.57	1.46	1.44	1.28	1.20	1.08	1.02
	Power / W	328.45	307.11	302.10	268.36	251.68	226.62	214.59
	T_{VL} / °C	51.4	55.2	58.7	63.9	68.9	77.4	87.5
2250	Speed / rpm	2252.6	2248.9	2250.8	2250.5	2250.0	2252.7	2250.2
	Torque / N·m	1.38	1.35	1.36	1.26	1.43	1.09	1.01
	Power / W	324.59	318.85	321.21	297.63	336.00	257.17	236.95
	T_{VL} / °C	51.7	55.1	58.5	64.2	69.2	78.1	88.0
2500	Speed / rpm	2499.9	2502.0	2501.0	2503.7	2499.8	2499.4	2502.3
	Torque / N·m	1.41	1.50	1.39	1.41	1.32	1.29	1.00
	Power / W	370.11	393.27	364.70	369.22	344.39	337.31	262.09
	T_{VL} / °C	51.3	54.9	58.6	64.4	70.2	78.9	89.0

Table C.33: Standard deviation of the sixth experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C						
		50	53.3	57.3	62.2	68.5	77.1	90
500	Speed / rpm	1.4	1.7	1.3	1.6	1.4	1.4	1.5
	Torque / N·m	0.22	0.26	0.25	0.25	0.24	0.25	0.24
	Power / W	11.62	13.38	13.29	13.11	12.79	12.98	12.45
750	Speed / rpm	1.3	1.3	1.4	1.1	2.1	1.3	2.0
	Torque / N·m	0.27	0.27	0.26	0.25	0.23	0.23	0.23
	Power / W	21.08	21.21	20.69	19.26	17.94	18.03	17.61
1000	Speed / rpm	1.1	1.4	1.4	1.1	1.3	1.1	1.3
	Torque / N·m	0.19	0.18	0.19	0.18	0.18	0.17	0.16
	Power / W	19.48	19.23	20.08	18.72	19.01	17.94	17.17
1500	Speed / rpm	1.1	1.3	1.8	1.4	1.2	1.4	2.0
	Torque / N·m	0.24	0.19	0.19	0.20	0.22	0.21	0.19
	Power / W	37.17	30.57	29.68	30.95	34.76	33.44	29.61
2000	Speed / rpm	1.8	1.4	2.4	1.4	1.6	1.5	1.4
	Torque / N·m	0.27	0.27	0.27	0.24	0.25	0.24	0.26
	Power / W	56.18	57.12	56.89	49.50	53.08	49.86	55.27
2250	Speed / rpm	1.4	1.1	1.2	1.1	1.3	1.4	1.0
	Torque / N·m	0.34	0.32	0.36	0.34	0.44	0.32	0.28
	Power / W	79.22	74.23	84.09	79.51	103.53	74.35	66.56
2500	Speed / rpm	1.1	1.5	1.8	1.7	1.3	1.4	1.4
	Torque / N·m	0.53	0.50	0.49	0.47	0.46	0.44	0.41
	Power / W	139.77	130.71	128.81	123.45	121.56	116.13	108.28

C.2.9 Rolling Bearings Power Loss results - Seventh Test

Table C.34: Seventh experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C
		50
500	Speed / rpm	500.0
	Torque / N·m	1.03
	Power / W	53.97
	T_{VL} / °C	49.9
	Q / $l\ min^{-1}$	0.14
750	Speed / rpm	750.
	Torque / N·m	1.32
	Power / W	103.50
	T_{VL} / °C	50.2
	Q / $l\ min^{-1}$	0.14
1000	Speed / rpm	1001.9
	Torque / N·m	1.41
	Power / W	147.53
	T_{VL} / °C	51.3
	Q / $l\ min^{-1}$	0.14
1500	Speed / rpm	1500.3
	Torque / N·m	1.51
	Power / W	237.04
	T_{VL} / °C	53.3
	Q / $l\ min^{-1}$	0.14
2000	Speed / rpm	2000.7
	Torque / N·m	1.50
	Power / W	314.57
	T_{VL} / °C	55.5
	Q / $l\ min^{-1}$	0.14
2250	Speed / rpm	2254.0
	Torque / N·m	1.44
	Power / W	339.92
	T_{VL} / °C	59.8
	Q / $l\ min^{-1}$	0.14
2500	Speed / rpm	2503.0
	Torque / N·m	1.84
	Power / W	482.04
	T_{VL} / °C	61.0
	Q / $l\ min^{-1}$	0.14

Table C.35: Standard deviation of the seventh experimental results for the rolling bearings - First test.

Speed rpm	Variable	Temperature / °C
		50
500	Speed / rpm	1.3
	Torque / N·m	0.24
	Power / W	12.55
750	Speed / rpm	1.8
	Torque / N·m	0.24
	Power / W	19.09
1000	Speed / rpm	1.3
	Torque / N·m	0.18
	Power / W	18.50
1500	Speed / rpm	1.3
	Torque / N·m	0.14
	Power / W	21.55
2000	Speed / rpm	1.2
	Torque / N·m	0.24
	Power / W	50.23
2250	Speed / rpm	1.7
	Torque / N·m	0.35
	Power / W	83.61
2500	Speed / rpm	1.9
	Torque / N·m	0.48
	Power / W	125.11