Sealing improvements by grease selection in double lip seals and labyrinth seals

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1 Introduction

Nowadays, many bearing systems are lubricated with lubricating grease. This lubricating grease is normally selected for the bearing operating temperature, running speed, load condition, and type of bearing contact. The only requirement regarding the seal is good compatibility with the seal elastomer material. However, in many systems it is not the bearing lubrication that determines the service life but the sealing performance against ingress of contaminants from the environment. Grease selection optimization regarding the sealing performance is therefore essential to further improve system service life.

Many textbooks on (grease) lubrication state that the grease increases the sealing performance. For example, the Automotive Lubricants Reference Book [1] gives as an advantage of grease that it prevents the ingress of dirt into the mechanism. Lansdown [2] states that “grease can form a very effective seal against ingress of dirt and other contaminants into the system”. According to them, contaminants are less likely to be transported through the bearing due to the semi-solid flow behavior of the grease. However, detailed knowledge on the mechanisms and the specific grease properties that provide this “sealing function of grease” is lacking. The selection of grease type for seal lubrication may have a big impact on mud and dust exclusion performance. This is due to differences in grease consistency and due the way the grease flows in a labyrinth seal during operation and a relubrication action

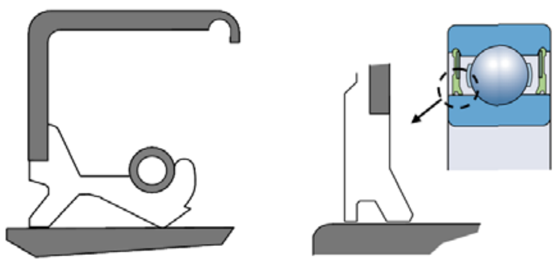
A series of experimental studies has been carried out by the authors to understand the grease flow behavior in straight channel flow and in labyrinth type seals (Westerberg et al. [3], Green et al. [4], Baart et al. [5], Li et al. [6]). Micro Particle Image Velocimetry technique has been used to determine the circumferential velocity of grease between sealing lips and to determine the axial grease flow through a labyrinth seal due to e.g. relubrication. The results help to understand where contaminant particles may settle down in the sealing system and show that grease does not flow in corners and narrow pockets, and strongly depends on the grease type and operating conditions. This understanding is important in order to design efficient geometries for double lip seals and labyrinth seals.

This paper presents a review of the experimental work on grease flow in sealing geometries and continues with a more in depth discussion on sealing improvements by grease selection in double lip seals and labyrinth type seals.

2 Grease flow measurements

2.1 Labyrinth and double lip seals

The study is focused on the grease flow in a "seal pocket" which represents the space between two sealing "restrictions". These restrictions can be either two contacting sealing lips, two non-contacting labyrinth restrictions, or a combination of both. Two examples of such systems are given in Figure 1. In Figure 1(a) the pocket width is large compared to the height and is therefore referred to as a wide pocket. In Figure 1(b) the pocket width is about equal to the pocket height and it is therefore referred to as a narrow pocket.



(a) (b)

Figure 1: Left, wide seal pocket and right, narrow seal pocket

The focus of this paper is on the grease flow behavior in the two different types of seal pocket geometries as indicated in Figure 1. It is assumed that at a certain moment, contaminant particles like dust, sand, or internal wear particles end up in the seal pocket between the sealing restrictions. The mechanism that brings the particles through the restriction into the seal pocket is not considered in the current work.

Three different greases are used with different NLGI grades. The NLGI2 grade grease is a general rolling bearing grease, the NLGI1 grade grease is a very soft rolling bearing grease (with higher base oil viscosity than the NLGI2 grease), and the

NLGI00 grease is a gear grease which is behaving close to a high viscosity oil. More detailed differentiation between the greases, also between greases with equal NLGI grade, can be made based on the measured rheology curves [5]. In this paper the three greases are only differentiated by the NLGI grade.

2.2 Micro Particle Image Velocimetry

To measure the grease velocity profile in a seal pocket, an experimental setup is used that allows for optical measurements inside the seal pocket. The velocity profiles are measured with a micro Particle Image Velocimetry (μPIV) system which consists of a high speed camera, an optical microscope, and a pulsed laser light source. The grease is seeded with small fluorescent particles that light up in the laser light. A single measurement consist of two images of the flow, separated by a time step Δt. A cross correlation method is used to calculate the displacement of small clusters of particles (interrogation areas) during the time step, and subsequently, the vector velocity field is calculated. The experimental setup and the μPIV method are described in more detail in Green et al. [4].

2.3 Circumferential grease flow

The experimental results presented in Baart et al. [5] show that in the narrow pocket, the velocity profile is significantly influenced by the side walls. Consequently, the flow should be modeled with a 2-dimensional numerical model. However, they use an analytical equation that describes the velocity profile at a defined distance from the wall. In the wide pocket it is assumed that the flow in the centre of the pocket is not influenced by the side walls such that it can be described by a 1-dimensional model. Figure 2 shows the measured velocity profiles and analytical equation for the narrow pocket together with the model results for the wide pocket. In Figure 2, the influence of the side walls in the narrow pocket is clearly visible.

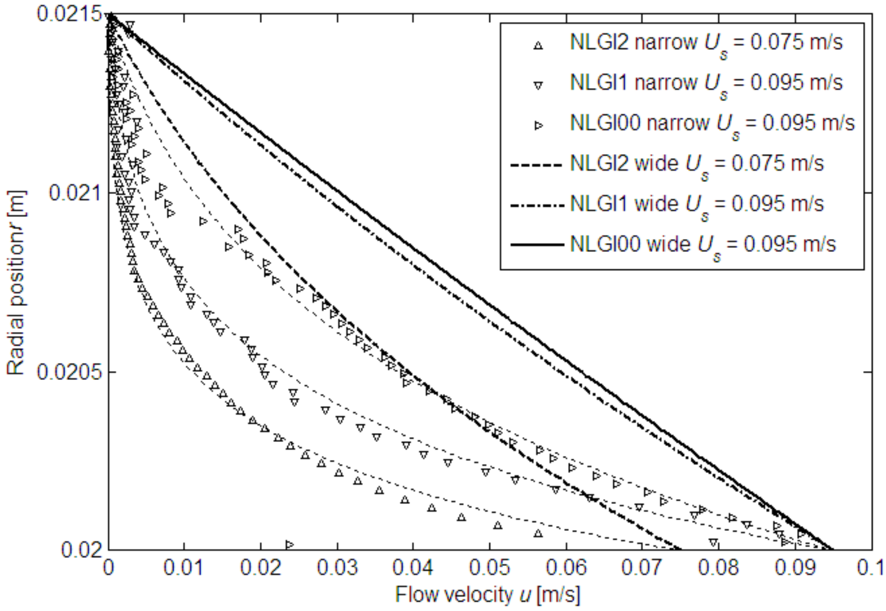
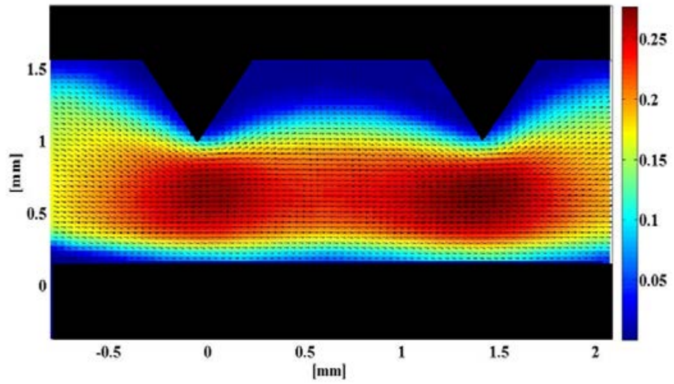


Figure 2: Grease velocity profile in a narrow and wide pocket. Symbols are experimental results and lines are model results.

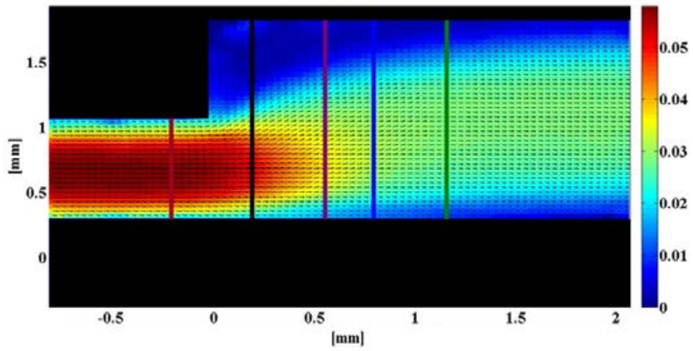
2.4 Axial grease flow

From the experimental results by Green et al. [4] it was observed that an axial grease flow through the pocket only takes place close to rotating shaft. This can be understood from Figure 2 where the velocity gradient in the narrow pocket, i.e. shear rate, is highest near the rotating shaft. Consequently, the grease viscosity will be lowest here due to shear thinning, and the grease close to the shaft will flow easiest in axial direction due to a pressure gradient.

In addition to the dynamic measurements, experiments were done without shaft rotation to simulate a relubrication action or a pressure difference due to e.g. cooling down of the bearing after running. Li et al [6] used the channel setup from Westerberg et al [3] to measure grease flow in a straight channel with restrictions. The straight channel with two restrictions, Figure 3(a), simulates a non-contacting seal with a narrow pocket as shown in Figure 1(b). From Figure 3(a) it becomes clear that also in this static case the grease flow mainly takes place close to the shaft surface and does not flow deep into the pocket volume between the restrictions. Figure 4 presents the flow depth as a function of flow rate for the three different greases. The flow depth is defined as the vertical distance between the lowest point of the restriction and the point where the flow velocity is smaller then $9 \cdot 10^{-3}$ m/s, exactly half way between the two restrictions.



(a)



(b)

Figure 3: Flow of NLGI 2 grade grease in a channel with restrictions.

Figure 3(b) shows the grease velocity when the grease exits from a long flat restriction into a wide pocket. Here the grease flow takes a certain length, approximately equal to the channel height, to fully develop again in a steady flow. The velocity profile resembles a plug flow as also discussed in Westerberg et al. [3]. Results of the steady flow for the three different greases are shown in Figure 5. Here the pressure drop was adjusted to reach similar flow velocities for the different greases. In addition the maximum flow velocity was normalized to compare the shape of the steady velocity profile.

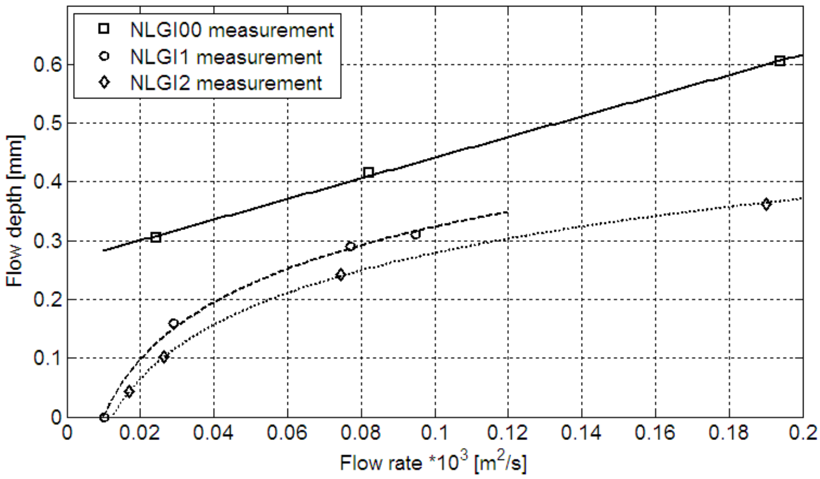


Figure 4: Penetration depth

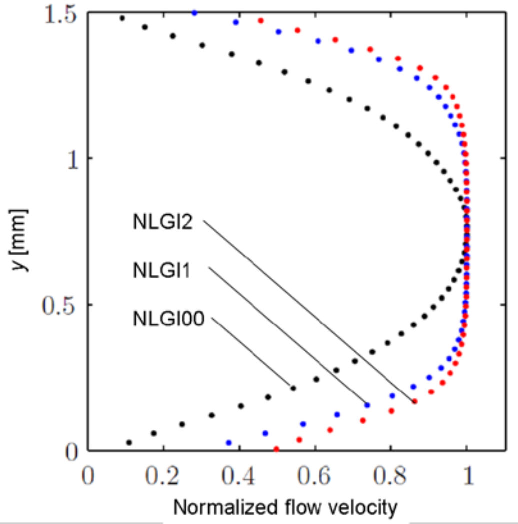


Figure 5: Developed grease velocity profile at *x* ~ 2 mm in Figure 3(b).

3 Contaminant particle migration

3.1 Radial contaminant particle migration

Solid contaminant particles that have entered into the seal pocket are assumed to move with the grease. Due to the high circumferential velocities, centrifugal forces act on the particles and force the particles to migrate to a larger radius. Baart et al. [5] used the velocity profiles from Figure 2 to model the particle migration in radial direction. Their model includes the centrifugal force on the particle and the drag force in the grease and reads

$$U_{p.r} = \frac{2}{9} a^2 \frac{1}{\eta_r} \left(\rho_p - \rho_g\right) \frac{U_\theta^2}{r} . \qquad (1)$$

In equation (1), a is the particle diameter, η_γ the shear rate dependent grease viscosity, ρ_p and ρ_f the particle and grease density respectively, U_θ the particle circumferential velocity, and *r* is the radius of the particle centre to the shaft center. In this equation, the particle circumferential velocity at radius *r* depends on the grease velocity profile. The grease viscosity is a function of the shear rate and therefore also a function of the grease velocity profile and radius *r*. Results of particle migration in radial direction, as a function of time in the different greases and pocket geometries, are presented in Figure 6. The results show that the radial position of the particle at a certain moment in time depends on both the pocket type and the grease type. For example after 10 hours, the particles in the wide pocket migrated to approximately the same radius for all greases while in the narrow pocket, the particle in the NLGI00 grease has migrated almost twice as far as the particle in the NLGI2 grease.

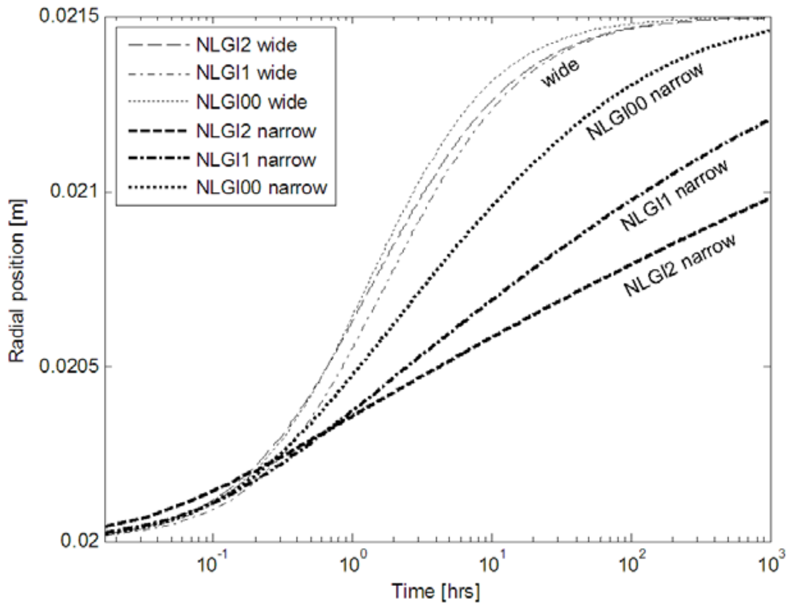


Figure 6: Radial position of a solid particle in the seal pocket as a function of time, grease type, and pocket geometry at 1 m/1 shaft speed.

3.2 Axial contaminant particle migration

Relubrication, heating up, or cooling down of the bearing and sealing system may result in a pressure difference over the sealing system. In such a case, the pressure can be released through the sealing contact and through the seal pocket. In the case of relubrication fresh grease may be forced through the sealing system by a pump. In this section the axial grease flow is related to the axial migration of contaminant particles as the particles will flow with the grease.

As shown in the experiments by Li et al. [6], in a narrow seal pocket, the distance between the restrictions is too small for the axial grease flow to fully develop. This means that part of the grease in-between the restrictions, i.e. the grease close to the outer wall, does not flow. Consequently, particles that have migrated in the radial direction, as shown in Figure 6, may not be picked up in an axial grease flow. In a wide seal pocket, where the width is much larger than the height, the grease flow will fully develop and pick up particles in the axial grease flow, except for the small volumes in the corners.

4 Discussion on sealing grease selection

In the previous sections, two phenomena have been described; the migration of particles in radial direction due to centrifugal forces and the migration of particles in axial direction due to a pressure difference or a relubrication action. The results clearly showed differences in behavior between the different NLGI grade greases. The effect on sealing performance will be discussed in this section.

4.1 Contaminant ingress

It was shown in Figure 6, that in the narrow pocket the particles migrate with different velocities for the different grease types. For example after 1 hour, a particle in NLGI00 grease has migrated ~0.47 mm into the narrow seal pocket while a particle in NLGI2 grease has migrated only ~0.36 mm into the narrow seal pocket. In addition, Figure 4 showed that for the NLGI00 grease, the flow depth is much larger than for the NLGI2 grease. This means that in the NLGI00 grease, the particle still may be picked up in an axial flow. For the example, the particles will only flow in axial direction when the flow rate is larger then $0.13 \cdot 10^{-3}$ m^2/s for the NLGI00 grease and $0.19 \cdot 10^{-3}$ m^2/s for the NLGI2 grease. Consequently, it can be concluded that after 1 hour of rotation, a higher flow rate is required to transport the particle in the NLGI2 grease than in the NLGI00 grease. To reach this higher flow rate, Westerberg et al. [3] showed that an approximately 3 times higher pressure difference is required for the NLGI2 grease to reach the same grease velocity as the NLGI00 grease. This means that the probability for a contaminant particle to ingress into the bearing, due to a pressure difference over the seal pocket, is lower for the NLGI2 grease than for the NLGI00 grease.

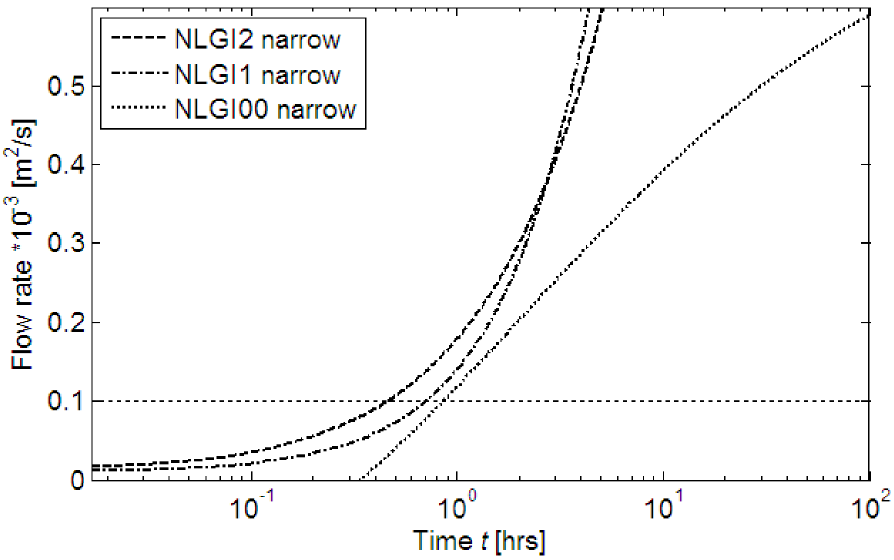


Figure 7: Required flow rate to force out all particles

In Figure 7, the results from Figure 3 and Figure 5 are combined to model the required flow rate for the particles to migrate in axial direction as a function of operating time. These results show that, at all times, the higher NLGI grade greases require a larger flow rate than the NLGI00 grade grease. After longer running times, the required flow rate (and thus pressure difference) increases significantly for the higher NLGI grade greases, which increases the sealing performance.

The small differences between the NLGI1 and NLI2 grease can be understood by considering the rheological behavior of both greases where the viscosity of the

NLGI1 grease is only lower than the NLGI2 grease up to a certain shear rate. Above this shear rate the effect of the higher NLGI1 base oil viscosity becomes dominating. More experiments will have to be performed to understand the relation between the rheological behavior and the flow rates more accurately.

4.2 Relubrication

In heavily contaminated applications, relubrication of the sealing system is used to force out contaminants and clean the system. In the case of wide pockets, where the grease flow can fully develop as indicated in Figure 3, this will work without flow rate limitations. Only a certain amount of grease has to be pushed through the seal pocket to refresh the old grease. In the case of a narrow pocket, the efficiency of such relubrication action is more complex and depends on the grease type used. Figure 7 can be used to evaluate the required flow rate during a relubrication action. The Figure shows that the required flow rates, to force out all contaminant particles, for the NLGI2 and NLGI1 grade greases are similar and increase very quickly at relubrication intervals longer than 1 hour.

Depending on the type of relubrication system, a certain volumetric flow rate can be achieved. The area flow rate, as used in Figure 4 and 7, then depends on the seal diameter. For example, a (re)lubrication system that delivers grease with a flow rate of 1000cc/min to a 80 mm diameter seal, generates a flow rate of $0.1*10^{-3}$ m^2/s. Figure 4 showed that the corresponding flow depth into the seal pocket is ~0.3 mm for the NLGI1 and NLGI2 grease and ~0.45 mm for the NLGI00 grease. In Figure 7 this $0.1*10^{-3}$ m^2/s line is indicated and can be used to estimate the required relubrication interval for a given flow rate. In the case the NLGI2 grade grease is used, a relubrication interval of half an hour is recommended, while in the cases of NLGI1 and NLGI00 greases, respectively 40 minutes and 50 minutes are recommended. These differences become more significant at lower flow rates.

5 Conclusion

Based on experimental results on grease flow in sealing systems, an evaluation has been done to better understand the effect of grease type on sealing efficiency. It can be concluded that, in the case of a wide seal pocket, the grease type makes no big difference in sealing performance. In the case of a narrow seal pocket, the grease type has a big effect both on the radial migration of contaminant particles and on the ability for particles to migrate in axial direction due to a pressure difference or relubrication action. The results indicate that higher NLGI grade greases provide better sealing as higher flow rates and pressure differences are required for particles to migrate into the bearing. In the case relubrication takes place, the higher NLGI grade greases require a more frequent relubrication to clean out the pocket.

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