Manuscript Title: Investigating Grease Behaviour in Tilted Double-Row Tapered Roller Bearing Installed in Wind Turbine by Developing a Full Scale Multi-Phase CFD Model

Journal: Wind Energy Science

Responses to Comments from Reviewer 3

Referee Comment:

325-329- The reader would like to follow the explanation of the author, about the interesting behavior, but lacks evidence from simulation images that substantiate the description. This must be added.
Author Response: Thanks for pointing this out. The redistribution phenomenon of grease cannot be easily visualized from the full-bearing simulation images due to their scale and complexity. Therefore, we believe that the graphs presented in figure 11 are the most effective way to demonstrate and quantify this behaviour
Follow up question: This is particularly important for a reader to derive measure on how to prevent such a behavior and will, in fact, provide potential for insights.

Author Response:

We agree that visual evidence is important to support the interpretation of redistribution behaviour and to help readers derive practical insights. However, a comprehensive qualitative understanding of the grease redistribution process can only be achieved either through a full 3D visualization of the post-processing results or through the inclusion of a very large number of images. To address the reviewer's request, we have attached (in the rebuttal only) representative images for the 45% grease filling ratio at different time steps for both the MFS and HS rows. These examples show that differences in grease occupancy between the two rows cannot be directly or unambiguously identified from qualitative visualization alone. Consequently, including these images (for all the cases) in the manuscript would substantially increase the page count without providing additional quantitative insight beyond what is already conveyed by Fig. 11 in the manuscript.

At this point, we kindly ask the reviewer and the Editor for guidance on how to proceed. The manuscript is already relatively long, and the journal applies page-based publication fees; with the current version, the budget allocated by our institution for this paper is almost exhausted. We would therefore appreciate suggestions for possible solutions that would allow the inclusion of additional visual material (e.g., via supplementary material or external links) without increasing the number of printed pages. Alternatively, we respectfully propose to keep this part of the manuscript unchanged.

Indeed, the grease distribution is quantitatively captured by the grease occupancy evolution shown in Fig. 11 in the manuscript, which clearly differentiates the behaviour of the MFS and HS rows over time. This representation allows the reader to directly assess both the rate and extent of redistribution, which are the key quantities relevant for grease distribution in tilted wind turbine bearings.

The redistribution behaviour can be attributed to the presence of bearing tilt, which introduces an asymmetric clearance and flow field. During the initial phase of operation, this geometric asymmetry dominates the transport process and leads to a rapid migration of grease toward the MFS row. As operation continues, a pressure gradient develops and subsequently governs the redistribution dynamics. In the absence of tilt, such asymmetric driving forces would be absent, and the observed redistribution behaviour would therefore not be expected to occur in a comparable manner.

The manuscript has been revised in accordance with the reviewer's suggestion and now includes a detailed explanation addressing this point.

(a) (b)

Figure 1: At time 0; Initial grease filling ratio

(a) (b)

Figure 2: At time 1 s: Grease distribution in a) MFS Row b) HS Row

(a) (b)

Figure 3: At time 2 s: Grease distribution in a) MFS Row b) HS Row

(a) (b)

Figure 4: At time 3 s: Grease distribution in a) MFS Row b) HS Row

(a) (b)

Figure 5: At time 4 s: Grease distribution in a) MFS Row b) HS Row

(a) (b)

Figure 6: At time 5 s: Grease distribution in a) MFS Row b) HS Row

(a) (b)

Figure 7: At time 6 s: Grease distribution in a) MFS Row b) HS Row

(a) (b)

Figure 8: At time 7 s: Grease distribution in a) MFS Row b) HS Row

Referee Comment:

Figure 11: The author should please make the spacing in the y-axis of each graph equal to make it easier to depict the differences between each case.
Author Response: Thank you. Figure 11 has been updated accordingly.
Comment: No, you have not.

Author Response:

Thank you for pointing this out. We apologize for the oversight in the previous revision. The y-axis spacing in all subplots of Fig. 11 has now been made identical, with consistent axis limits and tick intervals across all cases. This revision enables a direct visual comparison between the different conditions, as requested.

Moreover, an additional figure (Fig.12 in the manuscript) has been included in the manuscript showing the normalized grease occupancy with respect to each grease filling ratio. This representation enables a more direct comparison of the asymmetric grease distribution relative to its initial filling ratio.

Referee Comment:

330- Which value of alpha was used to detect a wetted cell? Anything >0? How do you treat a surface that has been wetted but is not wetted anymore?
Author Response: We used the alpha value of 0.5 which means that cells which had grease occupancy of 50 % or above were treated as wet.
Follow up: Thanks for adding the threshold. I currently cannot clearly understand how you are evaluating the wetting - is it by the wetting on surface patches or by volume fraction of grease for the first cell layer above the raceways? In the initial version, I understood it as the surface patch wetting but now you're talking about volume fractions of cells. Can you please clarify this?

Author Response:

We apologize if our previous replies were misleading; indeed, we acknowledge that an imprecise terminology was used, and we appreciate the opportunity to clarify our intended meaning more clearly here. To support the explanation, a 2D schematic has been added here, which helps illustrate the concept.

In the Volume of Fluid (VoF) approach, the solver assigns a volume fraction value, α, to each computational cell based on the fraction of grease volume relative to the total cell volume. Consequently, some cells have α = 1, meaning they are filled with 100% grease (red in the figure) and 0% air (blue in the figure), while other cells have α = 0, corresponding to 100% air and no grease. Intermediate values of α represent cells containing both phases according to the corresponding volume fractions.

In addition to computing the scalar value of α, which is a cell-based quantity, the solver also evaluates the gradient of α. This gradient (represented schematically by the vector n in the figure) provides information on how the grease–air interface is distributed within the cell. Therefore, beyond knowing the volume fraction of grease in each cell, we are also able to estimate its spatial distribution.

This distribution can then be projected onto reference surfaces. In the schematic, for example, considering the lower solid surface (shown in black), a surface value of the volume fraction, denoted as $\alpha^{(sup)}$, can be defined. This surface value does not necessarily coincide with the cell-centered α value, as it depends on the local gradient of α. As an illustrative example, for the cell highlighted in light blue, the cell volume fraction is α = 0.2, whereas the corresponding surface value is $\alpha_{(grease)}^{(sup)} = 0.55$. This means that although grease occupies only 20% of the cell volume, it is distributed over approximately 55% of the surface area, which can be inferred from the gradient information.

For the evaluation of wetted and non-wetted surface areas, we consistently referred to the surface-based volume fraction α rather than the cell-based volume fraction. We acknowledge that some confusion may have arisen in the manuscript and in the previous rebuttal. The $\alpha = 0.5$ threshold was introduced exclusively for visualization purposes in Figures 14–17, where only the grease phase is displayed, and it was not used in the calculation of wetted or non-wetted surface areas.

This clarification has now been explicitly included in the revised version of the manuscript to avoid any further ambiguity.

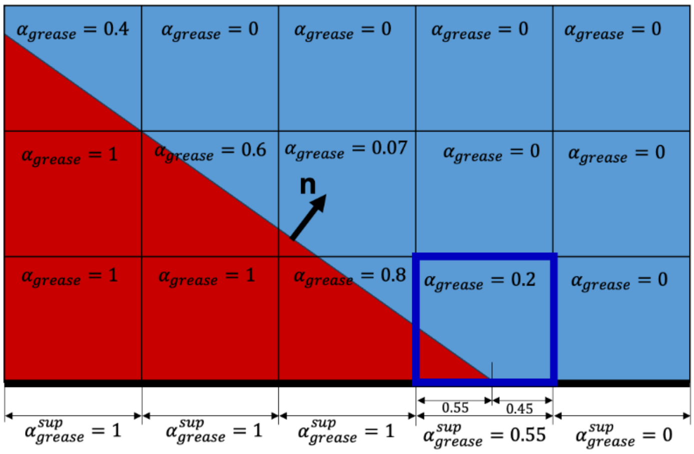

Figure 9: Illustration of VoF Model cell-centered volume fraction and surface-based grease fraction

Referee Comment:

Figures 12- Since you have the data for 7s, please add them to the chart. This will help substantiate your claims further.

Author Response: Thanks for this valuable suggestion. Basically, these graphs aim to investigate the time required for the grease to reach the topmost part of the bearing for different filling ratios and for different bearing components. Therefore, it is the time in which the grease reaches the top for each case. In some cases, the grease did not reach the top. It is explicitly mentioned in the manuscript.

Follow up question: The information of the 0.5 threshold was necessary for me to understand the paragraphs. I find the behavior of 12 c/45% filling and 12 d/45% & 35% particular and want to understand why there is a bump in the curve - numerical diffusion, the selection your threshold or a physical behavior? Or anything else?

Particularly your explanation of the next question of my initial review highlights the uncertainty in your approach and requires a through discussion in your paper and physical validation to render this method as valid.

Author Response:

We thank the referee for the careful examination of Fig. 12 in the manuscript. It is worth noting that the bump is observed only for the 45 % filling ratio and only on the outer raceway, while all other filling ratios and the inner raceway exhibit a smooth evolution. This clearly indicates that the effect is both regime and geometry specific, rather than a general numerical artefact. At a filling ratio of 45 %, the grease distribution on the outer raceway operates close to a regime in which the grease film is sufficiently developed to intermittently reach the upper circumferential region but remains sensitive to redistribution driven by the evolving pressure and shear field. This leads to a temporary accumulation of grease followed by partial redistribution, which manifests as a bump in the evaluated grease film angle. This behaviour can be observed in the following figures showing cells having 0.5 or above grease. For the MFS outer raceway, the grease film reaches a more advanced circumferential angle at 3 s, recedes at 4 s, and advances again at 4.5 s. In contrast, for the HS outer raceway, the grease film breaks down at 4.5 s.

On reviewer's recommendation, the explanation about the bump in the curve has been added in the revised manuscript.

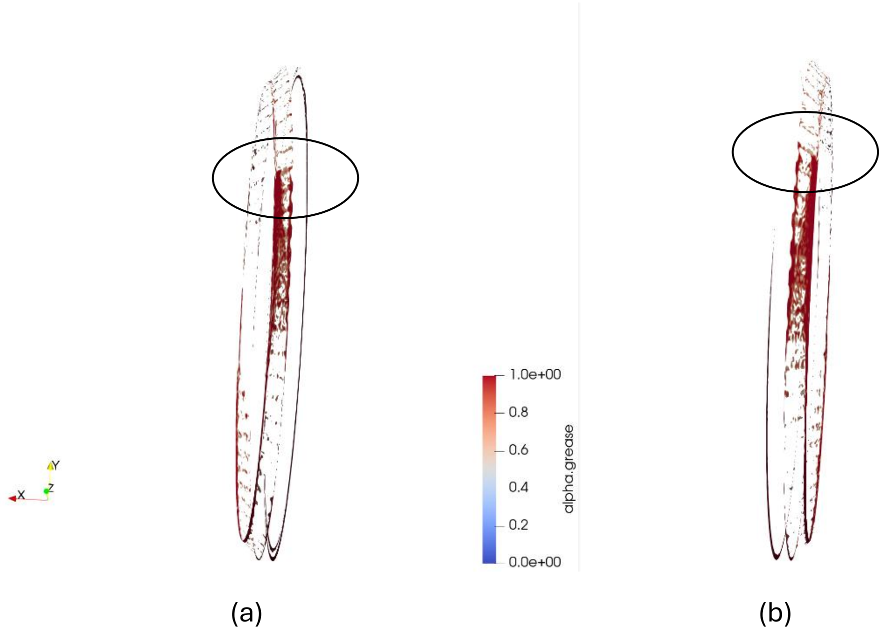

Figure 10: At time = 3 s; grease film evolution in a) MFS outer raceway b) HS outer raceway

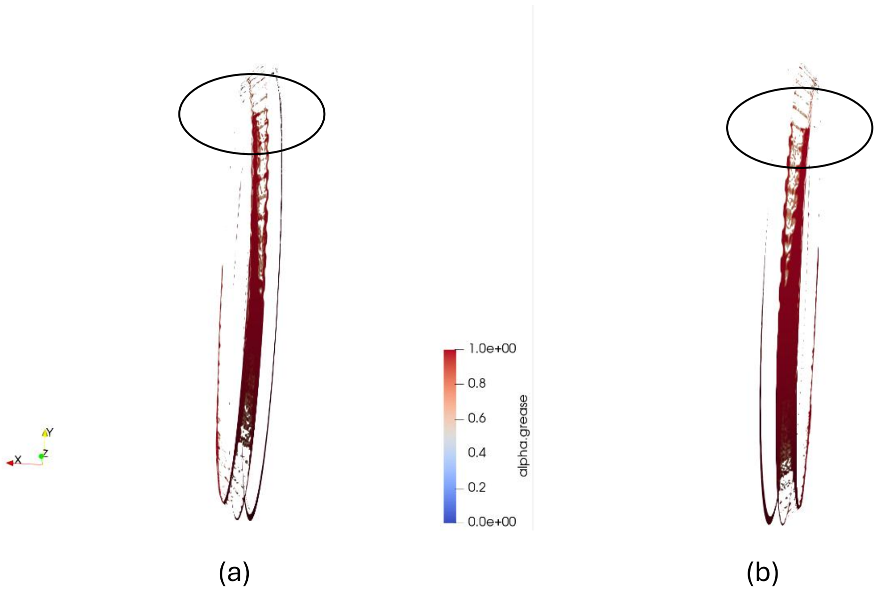

Figure 11: At time = 4 s; grease film evolution in a) MFS outer raceway b) HS outer raceway

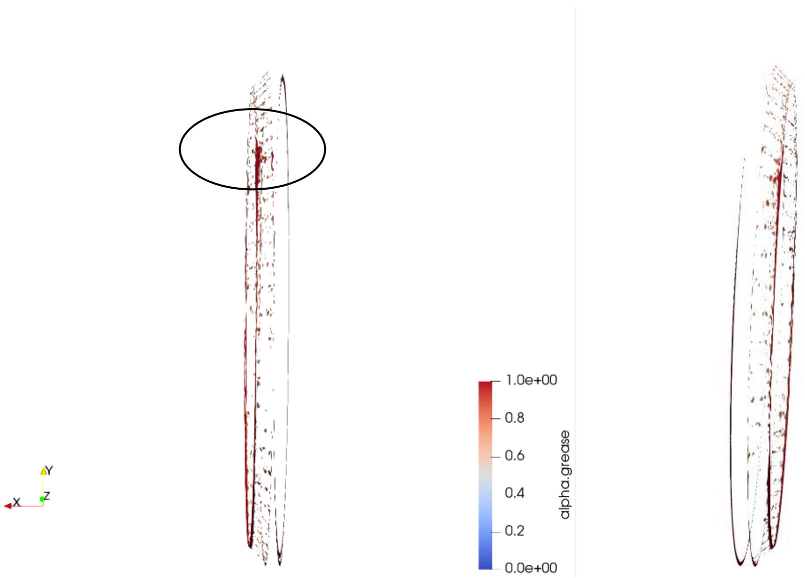

Figure 12: At time = 4.5 s; grease film evolution in a) MFS outer raceway b) HS outer raceway

Referee Comment:

355-359- Can you please highlight if there are noticeable differences in the fluid distribution between the different filling levels? Do we only see grease velocities or also mixture velocities? For these and the consecutive images, add an indicator of the rotational direction of the bearing.

Author Response: Thanks for the comment. Yes, there are differences in fluid distribution for filling ratios. In the figures, the velocity of mixture is shown. The difference can be illustrated in the zoomed portion of the figures. The indicator of rotation has been added in revised manuscript.

Follow up: Since we're considering a dynamic system (low dynamics, but still not stationary), the differences between the fluid field for different fillings is very subjective. Adding a representative free surface indication may help to identify differences or considering an averaged field.

Author Response:

We agree with the referee's recommendation. Following this recommendation, the fluid field visualization has been revised to reduce this subjectivity and to better highlight differences of flow fields between grease filling levels.

In the revised figures (Figs. 14 and 15 in the manuscript), the flow field is now visualized only in grease-dominated regions, by applying a threshold of grease volume fraction of 0.5 or above. This effectively provides a representative free surface indication and suppresses air dominated regions, allowing a clearer comparison of grease distribution and motion.

Using this approach, revised images for all three grease filling ratios are included. The differences in the flow fields between the filling levels are now more clearly highlighted, both in terms of spatial extent and velocity distribution, compared to the original mixture velocity visualizations.

Section 3.2 in the manuscript has been revised accordingly.

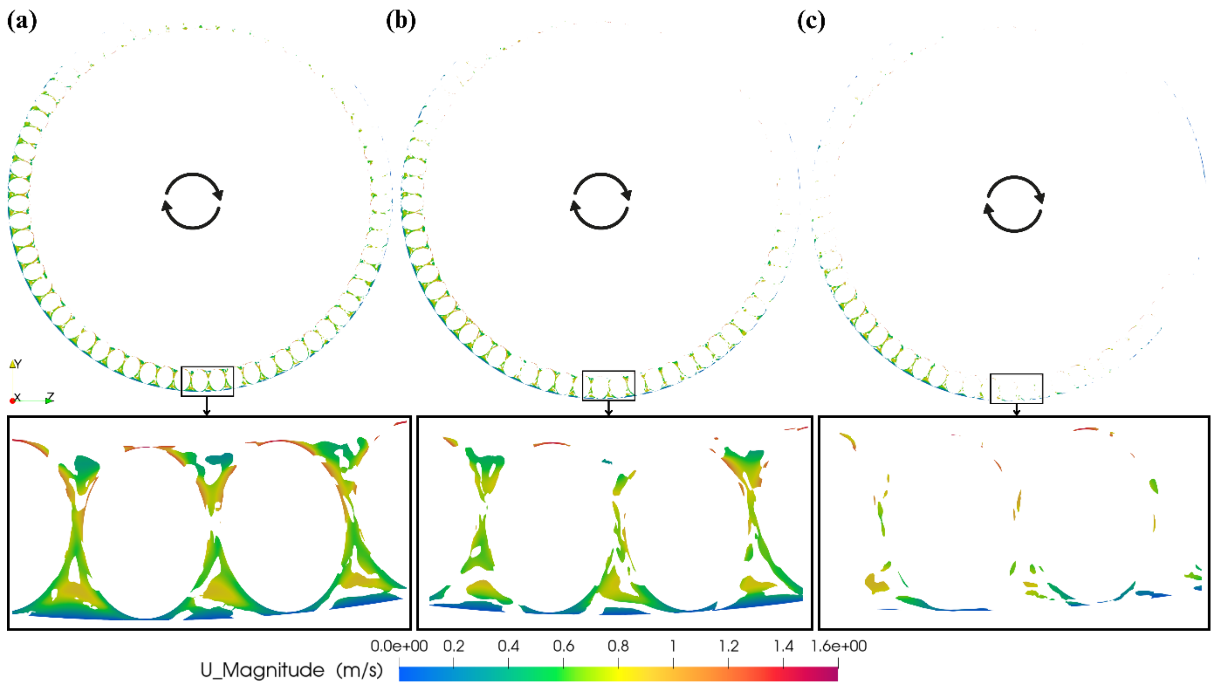

Figure 13: Fluxes of grease across MFS row after one rotation of cage a) 45% b) 35% c) 21%

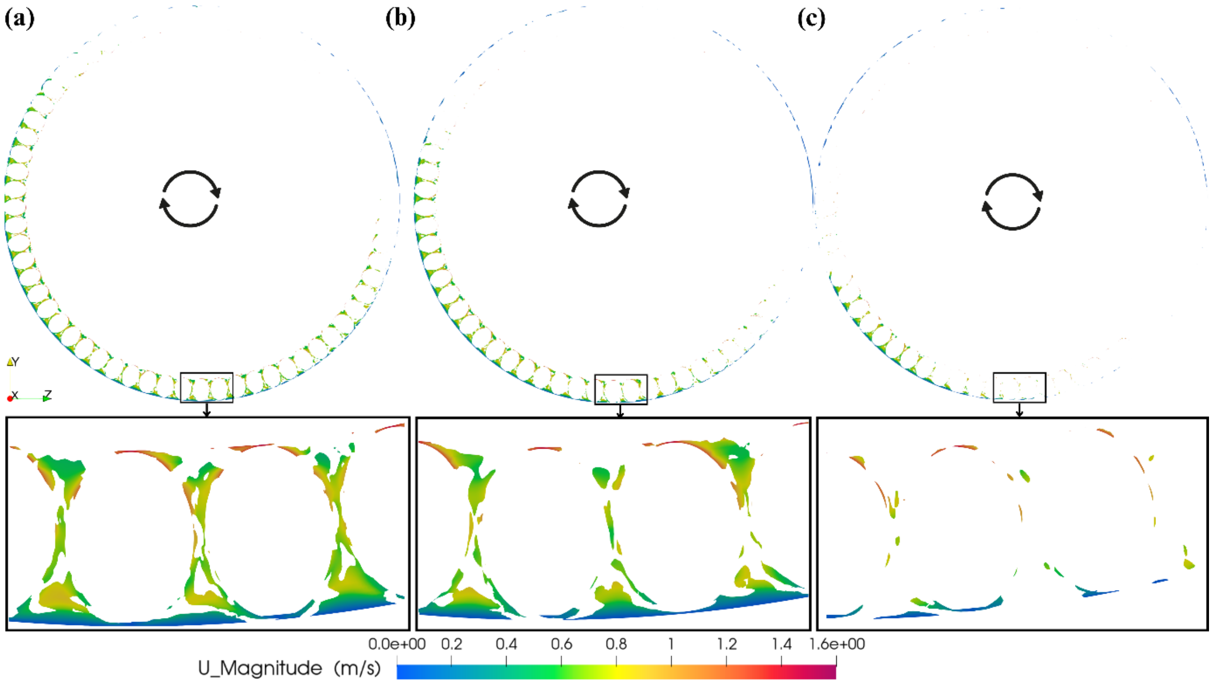

Figure 14: Fluxes of grease across HS row after one rotation of cage a) 45% b) 35% c) 21%

Referee Comment:

Referee Comment: Figure 15 & 16- It will be easier to depict the pumping effects if you change the colormap and make the range smaller. Please be precise in wording: the roller of the bearing will always displace fluid. Pumping means that the displacement has a favorable direction.
Author Response: Thanks for thee comment. The colormap in Figures 15 and 16 was already chosen with a narrow range to highlight pumping effects. Reducing the range further would, however, truncate the maximum grease velocities and misrepresent the full velocity field. We have updated the text in the revised manuscript accordingly
Follow up: Effectively, most areas of the axial velocities seem to be in the small velocity regime. Naturally, grease sticking on the tapered rollers will show positive/negative in- and outflow without actually being pushed to a side. So far, this section doesn't cover the displacement behavior properly. For the colormap: One could use a double log scale.

Author Response:

We agree with the referee that grease adhering to the tapered roller surfaces will naturally exhibit both positive and negative axial velocities, reflecting local in- and out-of-plane displacement rather than net transport. For this reason, the revised visualization does not rely on mixture velocities.

In the updated figures (Figs. 16 and 17 in the manuscript), the axial velocity field is visualized only in grease-dominated regions by applying a volume-fraction threshold of 0.5 or above which now shows the axial motion of grease only. The revised images show that in the regions between the rollers, the grease exhibits coherent axial velocities with a consistent directional bias. These regions are not directly attached to the roller surfaces and therefore cannot be explained solely by local roller induced displacement. Instead, they indicate a preferential axial transport of grease, which supports the presence of an axial pumping tendency under the given geometric and kinematic conditions.

Regarding the colormap, a double-logarithmic scaling was considered, but this did not improve the clarity or interpretability of the results. However, we have reduced the range of velocity fields in the revised figures, and it shows clear differences.

The manuscript has been revised according to the reviewer recommendations.

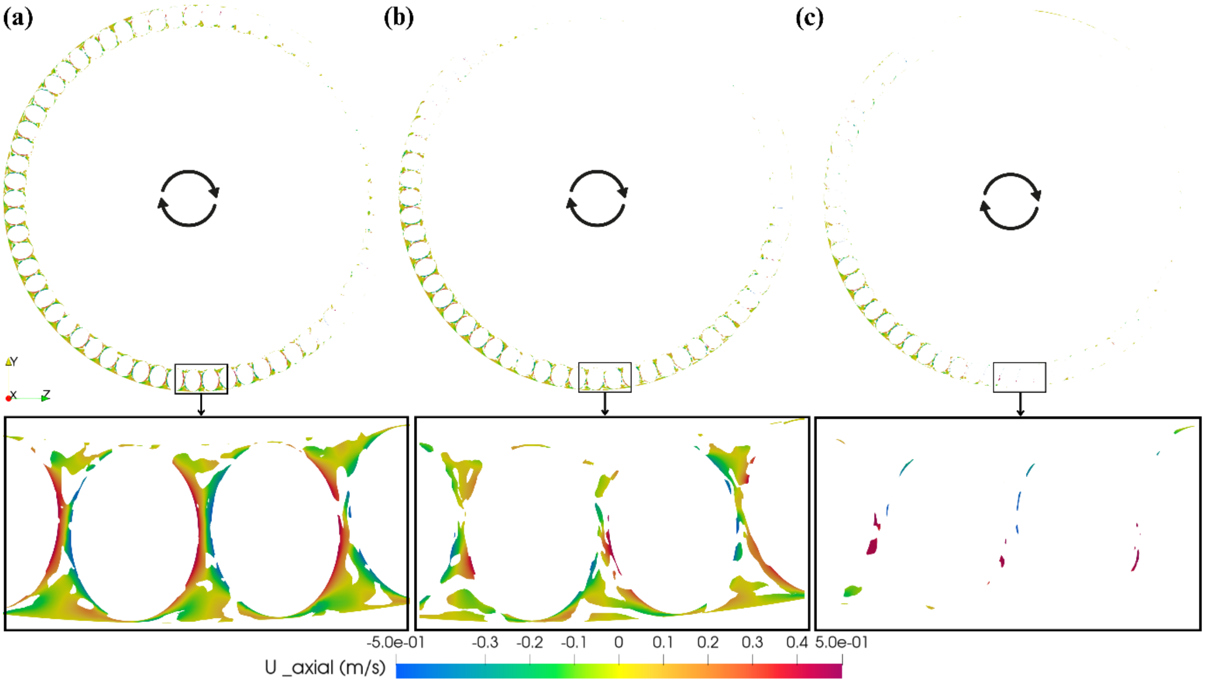

Figure 15: Axial velocity of grease across MFS row after one rotation of cage a) 45% b) 35% c) 21%

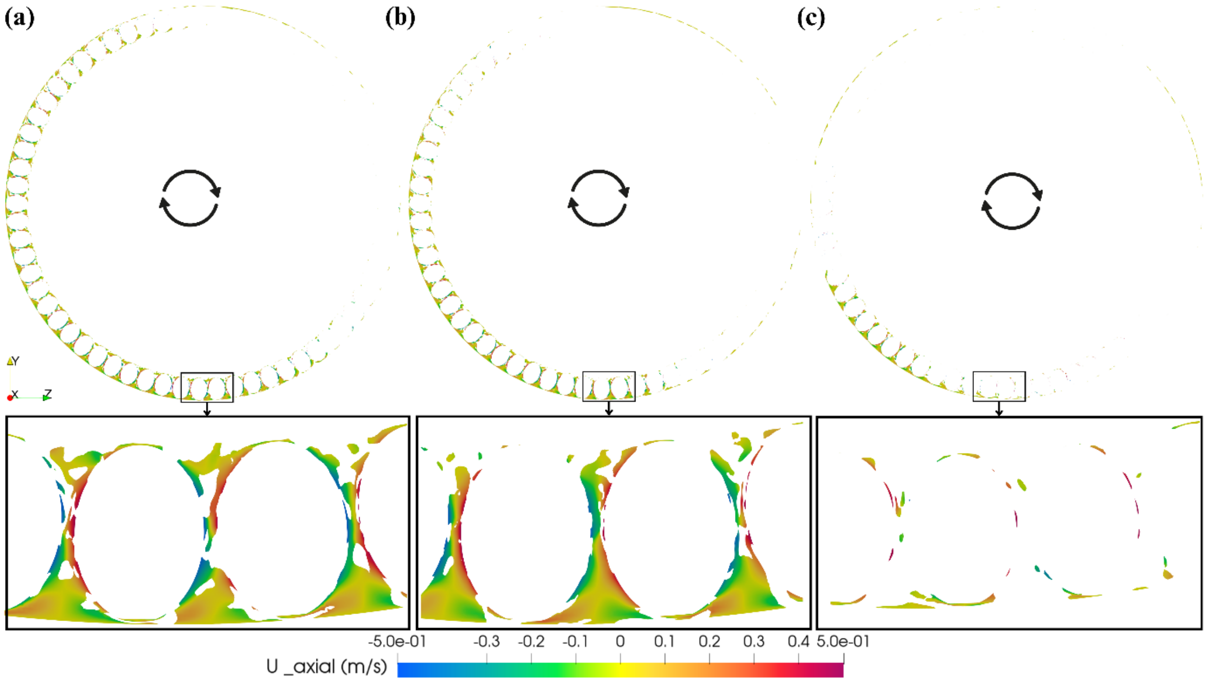

Figure 16: Axial velocity of grease across HS row after one rotation of cage a) 45% b) 35% c) 21%

Referee Comment:

Referee Comment: 375-379- By how much does sealing pressure increase with filling height? Are there overlinear effects? With the simulated pressure, are the sealings at risk of failing?
Author Response: It has been discussed accordingly in revised manuscript. The maximum pressure which seal of this bearing can withstand is 0.5 bar, whereas after simulation, we found that the maximum pressure on seals increases with the accumulation of grease or higher filling ratios. The region of maximum pressure varies with the filling ratio. For these filling ratios, the seals are in the safe limit. It has been concluded that for these filling ratios, there exists no risk of leakage.
Follow up: Again, are there over linear effects compared with the hydrostatic pressure?

Author Response:

Thank you for the comment. No over linear effects with respect to grease filling height are observed. The temporal evolution of the maximum total pressure acting on the seals for all investigated grease filling ratios is shown here in the figure below (Fig. 20 in the manuscript). The pressure represents the physically relevant load experienced by the seals under operating conditions. The results show that the maximum seal pressure increases smoothly with increasing grease filling ratio, without any indication of over-linear amplification. This behavior reflects the interplay between gravitational effects, which promote grease accumulation in the lower region of the bearing, and dynamic effects associated with rotation, which redistribute the grease circumferentially; these mechanisms partially counterbalance each other. During rotation, the location of the maximum pressure varies as the grease distribution evolves. However, since a significant portion of the grease is already located in the bottom region and additional grease migrates there as rotation progresses, the most highly pressurized region ultimately remains the bottom region of the bearing. Even when centrifugal and dynamic contributions are included, the resulting total pressure remains well below the sealing limit of 0.5 bar for all cases. Therefore, no over-linear effects relative to hydrostatic behavior are observed, and the seals are not at risk of failure for the investigated filling ratios.

This figure (Fig. 20) and explanation have now been added to the revised manuscript according to the reviewer recommendation.

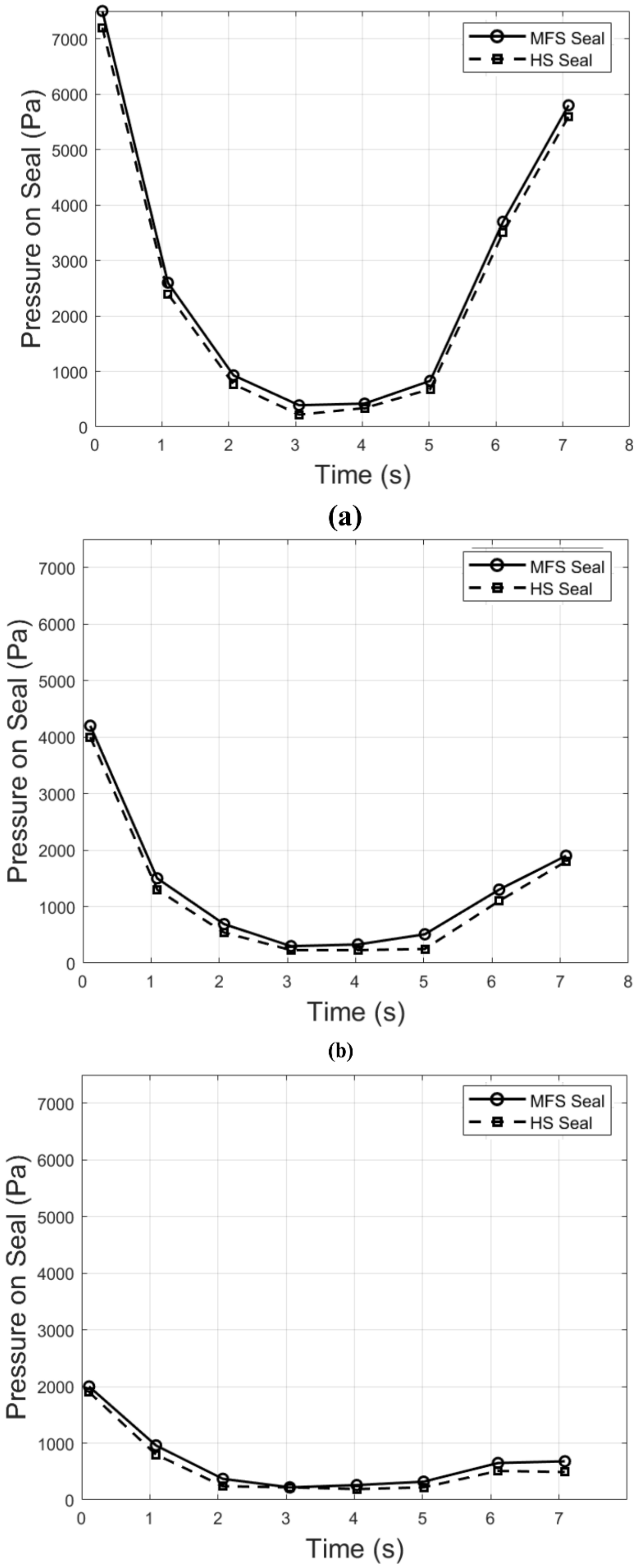

Figure 17: Temporal evolution of the maximum total pressure acting on the MFS and HS seals for a) 45% b) 35% c) 21%

Referee Comment:

Referee Comment: 380-386- This is an interesting study, but it lacks interpretation on why the grease is stuck in some upper region. Also, does it simply take more time to settle? Is this a reasonable outcome, or would we assume more mass wetting the bearing surface with time? Without proof, just gut feeling, 40s is fast for such a big bearing with a grease at 40°C; investigating the graph, the majority of the settling happens within the first 15s.
Author Response: Unfortunately, it is not possible to make a precise statement on this point. Since an interface capturing solver is used, the 2% volume is distributed over several cells and does not occupy at least 50% of any given cell. This means that the grease could be in contact with the surfaces, but the mesh resolution is not fine enough to confirm its exact position with certainty. The kinematic viscosity of grease drops drastically at 40 °C having value 450 mm^2/sec.
Follow up: So the remaining 2% could also partially be attributed to numerical artefacts as well?

Author Response:

Yes, the remaining grease volume of approximately 2 % can indeed be partially attributed to numerical artefacts associated with the interface-capturing approach. At such low volume fractions, the grease phase is distributed over multiple cells, and the interface becomes smeared due to numerical diffusion, making it difficult to unambiguously resolve thin surface films or small residual accumulations.

As a result, the precise spatial localization of this residual grease, whether it is in contact with the bearing surfaces or suspended in the bulk, cannot be determined with certainty at the present mesh resolution. This limitation primarily affects the interpretation of the final residual amount, rather than the overall distribution dynamics.

Referee Comment:

Referee Comment: 394 - 396 - I wonder if these findings could have been made without any simulation?
Author Response: The point raised is indeed relevant to the overall usefulness of the study. We agree that certain trends and behaviours could have been qualitatively anticipated based on experience, even without simulations. However, the use of numerical simulations allowed us to quantify them taking into consideration the fluid dynamic and the non-Newtonian behaviour of the grease.
Follow up: Thanks for the honest and transparent evaluation of the insights. I'd like to see more findings that a future reader can use to broader his knowledge about the grease migration process for wind turbine bearings based on such a simulation.

Author Response:

We appreciate the referee's constructive suggestion and agree that the value of the study should extend beyond confirming intuitively expected trends. While some qualitative tendencies could indeed be anticipated, the simulations provide several non-trivial insights that cannot be obtained without resolving the coupled fluid-dynamic and non-Newtonian behaviour of grease.

Specifically, the simulations allow us to (i) quantify the time scales of grease distribution and identify the dominance of the early transient phase, (ii) distinguish between geometry-driven (tilt-induced) and pressure-driven transport mechanisms and their temporal relevance, (iii) fluxes induced inside bearing (iv) evaluate how filling ratio influences pressure distribution on sealings and (v) assess the spatially resolved wetting evolution on raceway surfaces, which cannot be inferred from global considerations alone.

These findings provide detail understanding that goes beyond qualitative reasoning. All simulations in this study were performed using the current bearing geometry, and that no alternative geometries were investigated. Consequently, the present work does not aim to assess the impact of geometric modifications or to propose design optimization strategies.

Nevertheless, the focus of this study is on understanding the influence of operating parameters i.e., such as grease filling ratio and rotational effects on grease distribution and migration within the bearing. These parameters provide valuable insight into the bearing's operating behaviour under realistic conditions, independent of geometric variation. Such understanding is a prerequisite for informed design decisions and can serve as a foundation for future studies that explicitly address geometric optimization.

In future, this study would be extended in finding the load independent power losses and contribution of different rotating components in these losses.

Referee Comment:

Referee Comment: 404-405- Please include the experimental validation to highlight the validity of your method for this field.
Author Response: The test bench is currently under design, and its construction is planned to be completed by the end of 2027. For this reason, it is not possible to include experimental results in the present work. However, we are confident that these results will be available and discussed in a future study.
Follow up: I fear this renders the outcome and impact of the content as vague. If leakage is observed in the experiment or no damages on the rollers, one would have to redo the full story. I hope you understand that experimental validation for a novel approach is necessary to accept the method as valid.

Author Response:

We fully understand the referee's concern regarding experimental validation and agree that experimental evidence is ultimately essential to quantitatively assess leakage and damage mechanisms. However, we would like to clarify the scope and intent of the present work. This study does not aim to provide a final or complete validation of leakage or damage risk, but rather to introduce and demonstrate a numerical framework for analysing grease distribution, internal fluxes, and sealing pressure in large bearings under realistic operating conditions.

The validity of the proposed approach is supported by several factors. First, the governing equations, numerical methods, and rheological models employed are well established and widely used in multiphase lubrication and grease flow simulations. Second, the observed trends, such as redistribution driven by tilt-induced asymmetry, the development of pressure gradients, internal grease fluxes, and the influence of filling ratio, are physically consistent and align with theoretical considerations and experimental observations reported in the literature. Third, the simulated sealing pressures remain within known operational limits of the sealing system, providing an important sanity check against unphysical or unrealistic predictions.

We acknowledge that dedicated experiments are required to quantitatively assess leakage or component damage and to further calibrate model parameters. Nevertheless, the absence of experimental results in the present work does not render the outcomes vague. The manuscript does not claim predictive certainty for failure or damage but instead provides insights that are directly relevant for understanding grease migration behaviour and its implications for bearing operation. Importantly, potential experimental outcomes, such as the presence or absence of leakage, would not invalidate the numerical framework itself but would serve to refine and extend it in future studies.

In the presence of seal leakages, the present study should be regarded as a diagnostic tool rather than a direct design solution. Specifically, the proposed approach enables an assessment of whether observed leakages can plausibly be attributed to static or operating overpressure effects, or whether these mechanisms can be reasonably excluded as the primary cause.

In this sense, before pursuing tighter design tolerances, modifying seal geometry, or introducing additional instrumentation, the model can be employed to evaluate whether overpressure is likely to be responsible for the leakage. If overpressure effects are found to be insufficient, attention can then be directed toward alternative causes, such as manufacturing tolerances, material degradation, or assembly-related issues.

In addition, this study was conducted in collaboration with a wind turbine manufacturer. All simulations were performed under operating conditions representative of those most commonly encountered in practice by the company.