Advanced Gearbox Lubrication Analysis: A Virtual Lab for Design Optimization

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For over two decades, our Montreal-based engineering simulation consultancy has provided advanced solutions to a diverse range of industries. Our expertise has facilitated the resolution of complex engineering challenges, leveraging the latest technologies in computational fluid dynamics (CFD) and heat transfer analysis. Among our recent projects, one particularly notable case involved a company specializing in converting combustion engine vehicles to electric vehicles. That company developed a compact electric motor paired with a 2-speed gearbox, illustrated in Figure 1, designed to optimize performance and efficiency.

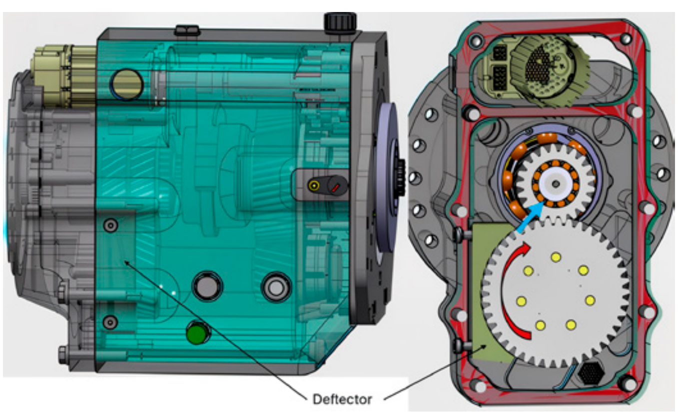


Figure 1—Two-speed gearbox isometric and cutaway views showing the deflector.

During the development process, the manufacturer identified a critical region that could lead to an overheating bearing problem. Figure 2 shows a cut view centered on the narrow gap between the second gear and the input gear. Anticipating this problem, the manufacturer added a deflector to their design. The goal was to guide more lubricant toward the narrow gap to induce better cooling of the bearing. They built a test bench and faced the anticipated problem.

Despite the deflector, they observed some damage on the input gear bearing. Paint labels were placed on the neighboring gears and indicated high temperatures confirming the overheating problem. To expedite the iteration process and identify a viable solution, the client sought our assistance to develop a comprehensive analysis workflow that could replicate the problem and test potential solutions efficiently.

Our first objective was to reproduce the problem, by simulating the exact same configuration as the one on their test bench. Once correlated, we could investigate the results, understand the lubricant behavior and test several concepts to solve the overheating problem. This case presented an excellent opportunity to demonstrate the capabilities of advanced simulation techniques in addressing real-world engineering problems, ultimately contributing to the company's success in developing reliable and efficient products.

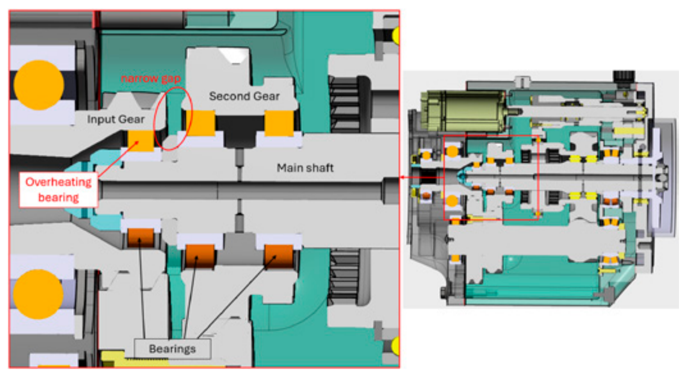


Figure 2—Cutaway view of the gearbox, zoomed on the narrow gap region.

Experimental Test Bench Challenges

The process of constructing a gearbox prototype is both time-consuming and costly. Each new design requires a unique set of components, often necessitating specialized manufacturing procedures. The lead time for producing these components can be extensive, encompassing material procurement, machining, assembly, and quality checks. Additionally, the cost associated with manufacturing a single prototype is high, as the procedures do not exist yet and the machinery might not be adapted.

Once a prototype is built, any design changes mean starting the process over again. This iterative cycle can be exceedingly slow, with each iteration requiring new parts, leading to significant delays in the development timeline. The slow pace of physical prototyping makes it challenging to quickly test and refine new design concepts, ultimately slowing down innovation and optimization efforts.

Extracting precise engineering data from a physical test bench is another major hurdle. The dynamic and complex nature of gearbox operation makes it difficult to gather accurate and comprehensive data, essential for informed design decisions.

One of the primary challenges is visualizing the behavior of lubricant within the gearbox. Lubricant splashing, crucial for cooling and lubrication, occurs rapidly and chaotically, making it difficult to observe and analyze. Windows in casings and high-speed cameras are sometimes used to capture these dynamics, but these methods have limitations. The visibility inside the gearbox is restricted, and the high-speed cameras required for capturing fast events are expensive and can only provide limited views.

Churning loss, the resistance created by lubricant splashing against rotating parts, is a critical factor affecting gearbox efficiency. Accurately measuring churning loss in a physical test bench is challenging. It requires precise instrumentation capable of capturing the subtle differences in torque. The sensors and equipment needed must be carefully calibrated and maintained to ensure accuracy. Torque loss measurement is the sum of the churning loss, the bearings loss, seal friction losses and the gears friction, making churning loss only estimation challenging.

Temperature measurement on fast-rotating parts and small bearings presents another significant challenge. Thermocouples, sensitive paint and labels are commonly used, but placing these sensors on moving parts is complex. Ensuring that the sensors remain in contact and provide accurate readings while the parts are in motion is difficult. Additionally, the small size of bearings and the high rotational speeds make it hard to obtain precise temperature data. Usually, a paint label can be placed on a neighboring shaft, but not on the bearing itself. And it is telling you if the temperature has reached a certain threshold but does not give you the value.

The challenges associated with physical gearbox test benches underscore the limitations of traditional prototyping and testing methods. The time and cost of building prototypes, combined with the difficulties in extracting accurate engineering data, significantly hinder the efficiency of the development process. These challenges highlight the need for advanced simulation techniques and virtual models, which can provide a more efficient, cost-effective, and comprehensive approach to gearbox design and analysis. By leveraging these technologies, engineers can rapidly iterate designs, test multiple conditions and scenarios, and extract detailed insights without the constraints of physical prototyping.

Numerical Challenges in Modeling Gearbox Lubrication

Numerically, modeling gearbox lubrication involves significant challenges. Lubricant splashing is a highly turbulent and transient process, necessitating a transient CFD analysis with a sufficiently long simulated time to achieve a developed flow. This typically requires four to eight seconds of physical time, depending on the geometry's size and complexity, and demands substantial computational power. The new XFlow 2023 solver supports both NVIDIA and AMD GPU cards, allowing for significantly reduced runtimes, from weeks of computing time to days, making this process accessible. XFlow employs a particle-based Lattice Boltzmann solver, offering multiphase and moving parts modeling capabilities, irrespective of the system complexity, gear types and lubrication methods (Ref. 1).

Heat transfer, being a slower process, is typically resolved through steady-state analyses. The Abaqus implicit solver is widely recognized in both industry and academia for its effectiveness. Lubrication involves heat extraction from solid parts through convection, a challenging aspect to quantify in transient analyses with rotating parts. The equation for convection, also known as the heat transfer convection equation, is typically expressed by Newton's law of cooling. This law describes the heat transfer between a surface and a moving fluid. The equation is as follows:

$$Q = h * A * (T_s - T_f) \tag{1}$$

where

Q is the rate of heat transfer (in W)

h is the convective heat transfer coefficient, HTC (in $W/(m^2 \cdot °C)$)

A is the surface area in contact with the fluid (in m^2)

T_s is the temperature of the surface (in °C)

T_f is the temperature of the fluid far from the surface (in °C)

The convective heat transfer coefficient (h) is evaluated during the transient CFD analysis at every time increment, on all surfaces. The values of h are highly uneven across the circumference of the gears due to their rotation and the turbulent nature of the splashing. To use these values in a steady-state heat transfer analysis, the h values at each finite element node must be averaged over their respective displacements. Rotating parts are represented by hundreds of thousands of nodes, making the data processing and transfer from a transient CFD analysis to a steady-state heat transfer analysis a major challenge.

In the company's project, we faced these numerical challenges head-on. The process required meticulous discretization of gear profiles and the modeling of roller and ball bearings, involved using advanced post-processing tools and visualization techniques, along with automating data processing. Utilizing advanced solvers and leveraging our GPU card power enabled us to overcome these challenges, providing reliable and actionable insights into the lubrication issues and potential solutions.

Simulation Workflow Development: Building the Virtual Model

Developing an analysis workflow for gearbox lubrication involves several critical steps that must be meticulously executed to ensure accurate and reliable results. The process begins with CAD preparation in Dassault Systèmes 3DExperience using CATIA applications.

CAD Preparation

If the geometry is not native to the 3DExperience platform, it needs to be imported, with STEP files being the most robust option. Once imported, the assembly must be filtered to retain only the relevant parts for the lubrication simulation. Bolts, rivets, and parts not in contact with the lubricant should be removed. Unnecessary features, such as bolt and rivet holes, must be defeatured to avoid small vertices, unsuitable lattice sizes, and poor resolution. The casing, typically composed of several parts, should be merged to create a single watertight envelope. This is crucial for XFlow's lattice generation to accurately recognize fluid domain boundaries. To expedite the CFD scenario definition, it is recommended to group parts rotating at the same speed into the same sub-assembly, allowing the equation of motion to be set once.

Modeling bearings poses a challenge due to their many separate moving parts, such as balls or rollers. A simple donut shape would prevent any lubricant movement across the bearings. Bearings could be considered as porous zones, but this approach requires calibration and experimental data or a specific analysis. Given XFlow's proficiency in handling rotating parts, we decided to model each ball and roller within the main bearings. The motion of ball or roller is complex, as each rotates around its own center. To simplify the setup, we applied a uniform motion equation to all balls or rollers, averaging the velocities of the bearing's external (V_e) and internal case ((V_i)) : (V_e+V_i)/2.

Once the relevant parts are selected and defeatured, the assembly is reorganized, and the casing is made watertight. The parts are then ready for meshing.

Discretization

Having a unified shared mesh is crucial for accurate data transfer between the CFD and heat transfer analysis. In the CFD analysis, discretization involves representing a continuous solid in a tessellated environment. Spherical and cylindrical shapes must be finely discretized to ensure realistic interactions with the fluid. A coarse mesh would create a rough interface, leading to excessive interaction with the fluid.

For the heat transfer analysis, meshing serves to represent continuous parts within an element-based solver. A mesh that is too fine demands more computing power, primarily RAM, and increases runtime. Additionally, it requires longer data processing to map the heat transfer coefficient accurately. Meshing solid parts involves discretizing them for the conduction equation, balancing the need for detail with computational efficiency. The equation of conduction, also known as Fourier's law of heat conduction, describes the rate at which heat energy is transferred through a material due to a temperature gradient. For three-dimensional heat conduction, Fourier's law is expressed as:

$$q = -k\nabla T \tag{2}$$

where:

- Q is the heat flux vector (in W/m²)
- k is the thermal conductivity of the material (in watts per meter per degree Celsius, W/(m·°C))
- ∇T is the temperature gradient vector (in °C/m)

Since the equation is linear, the element order can also be linear. We mostly utilized tetrahedral linear elements, applying an absolute sag criterion to refine areas with small radii to capture finer details. The bearings were meshed with linear hexahedral elements. The specific mesh size was determined to balance accuracy and computational efficiency. In total, we had nearly one million elements. This mesh information is then transferred to XFlow to construct the CFD analysis scenario.

Transient CFD Scenario Definition

Setting up the scenario in XFlow takes less than an hour for the user. A turbulent multiphase transient analysis is defined, considering incompressible flow. The Lattice-Boltzmann method in XFlow uses the Wale-Adapting Local Eddy (WALE) turbulence model. The gravity effects are specified by an acceleration constant in the vertical direction. The lubricant was 75W140 oil with properties defined at 85°C. The initial lubricant level is set by specifying a coordinate in the vertical direction, representing 2L of lubricant inside the gearbox. The motions of gears and bearings are defined using angular velocity equations over time. The input gear rotates at 6000 RPM.

The minimum lattice dimension is determined based on the narrowest region where the lubricant flow needs to be captured. A visual of the lattice used in the analyses is shown in Figure 3. To ensure an accurate velocity gradient, at least three to five lattice volumes should be present in the narrowest region, indicated by the red arrow. Local refinement regions must be defined carefully to fully encapsulate the entire rotating body; otherwise, the solid-fluid interface will not be modeled accurately.

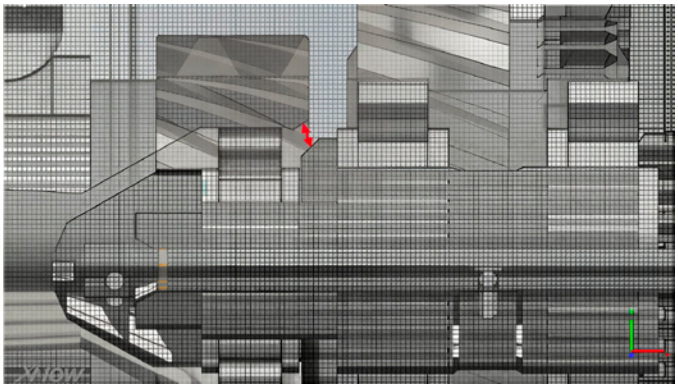


Figure 3—Lattice representation around the narrow region of the overheating bearing.

The time increment is defined by the smallest lattice volume and the highest solid tangential velocity:

$$dt = \frac{l}{v * 10\sqrt{3}} \quad (3)$$

where:

dt is the time increment (in s)
l is the lattice size (in m)
v is the tangential velocity (in m/s)

The total simulation time is based on the geometry's size and should be set to ensure that the flow is fully developed and stabilized. If the initial simulation time is insufficient, a restart can be performed to extend the total time. Monitoring the analysis during computation helps determine when the flow has fully developed. Using the NVIDIA GV100 card, it took 32 hours to simulate one second.

Transient CFD Results Analysis and Data Processing

While the analysis is running, the user can monitor scalar variables through graphs. To determine if the flow is fully developed, key values such as torque on rotating parts and lubricant volume within specific regions should be observed. These variables should stabilize and tend towards a fixed value to confirm that the flow has reached a steady state. Due to the highly turbulent nature of the splashing, some oscillations may appear and must be interpreted carefully. However, there should be no significant variations or trends indicating an increase or decrease. Figure 4 illustrates the distribution of the lubricant in different volumes of the gearbox. After 2 seconds, around 56 percent of the lubricant is inside the rear half, and 57 percent is in the half left.

On the graph, a transient phase is evident during the first second with important oscillations, before the flow begins to stabilize.

Once the flow is confirmed to be fully developed, the first post-processing phase begins. At this stage, a wealth of information can be extracted prior to the heat transfer analysis. Qualitative insights are derived from the generated animations, which offer valuable visuals inside the gearbox, revealing details that would otherwise be impossible to observe. In Figure 5, the left image shows a global cut view of the gearbox with a colored representation of the lubricant velocity. The right image shows a cut view in another direction, allowing for visualization of the lubricant movement close to the overheating bearing. These visuals serve as a first qualitative indicator to evaluate the lubrication efficiency.

Visualizing the flow velocity, dark areas are noticed above the deflector. It seemed that the flow was obstructed by the deflector, and very little was directed towards the overheating bearing. We tried removing the deflector.

Figures 6 and 7 present a comparison of the lubricant movement with (left) and without (right) the deflector.

The red bent arrow tells the rotation direction of the intermediate gear. In the left image, the darker areas above the deflector and next to the gearbox floor indicate lower lubricant velocity, which could indicate some recirculation pockets inducing inefficient cooling. In the right image, without the deflector, the lubricant velocities are higher, suggesting that the lubrication should be more efficient. Without the deflector, the lubricant flows faster closer to the gearbox floor, moves up faster against the left wall and more lubricant seems to come in contact with the overheating bearing.

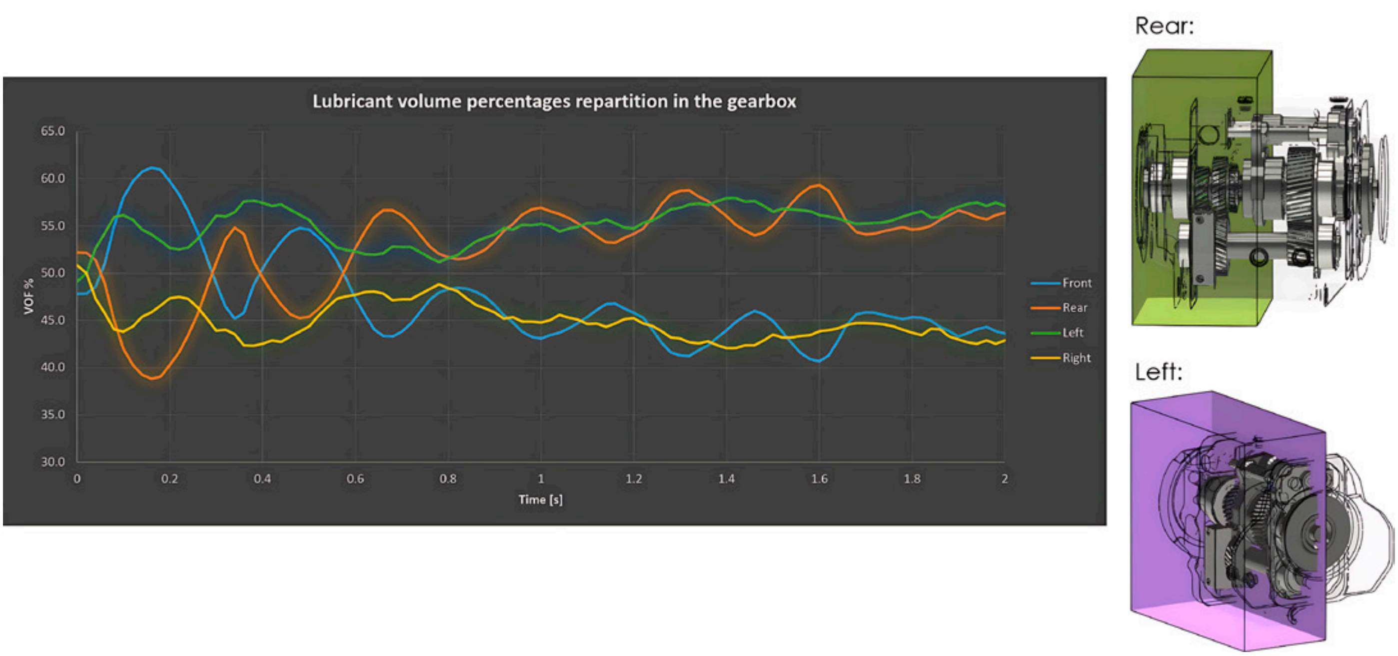


Figure 4—Graph showing the distribution of lubricant inside different volumes of the gearbox, the right images illustrate the rear and left volumes.

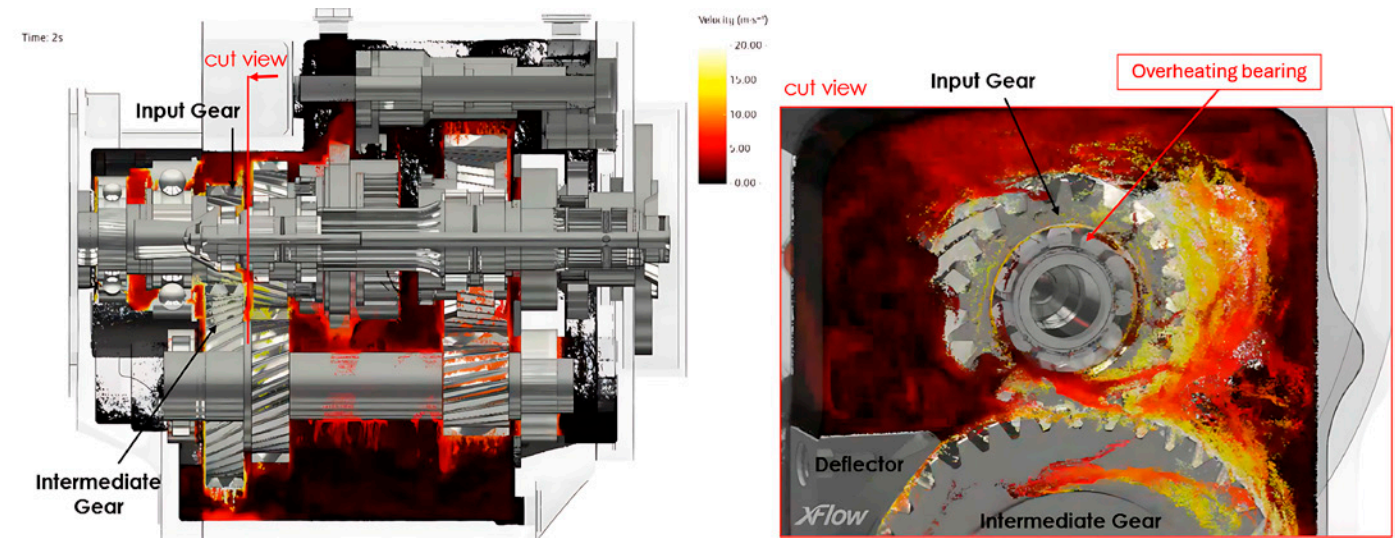


Figure 5—Cut views inside the gearbox with colored visualization of the lubricant movement close to the overheating bearing.

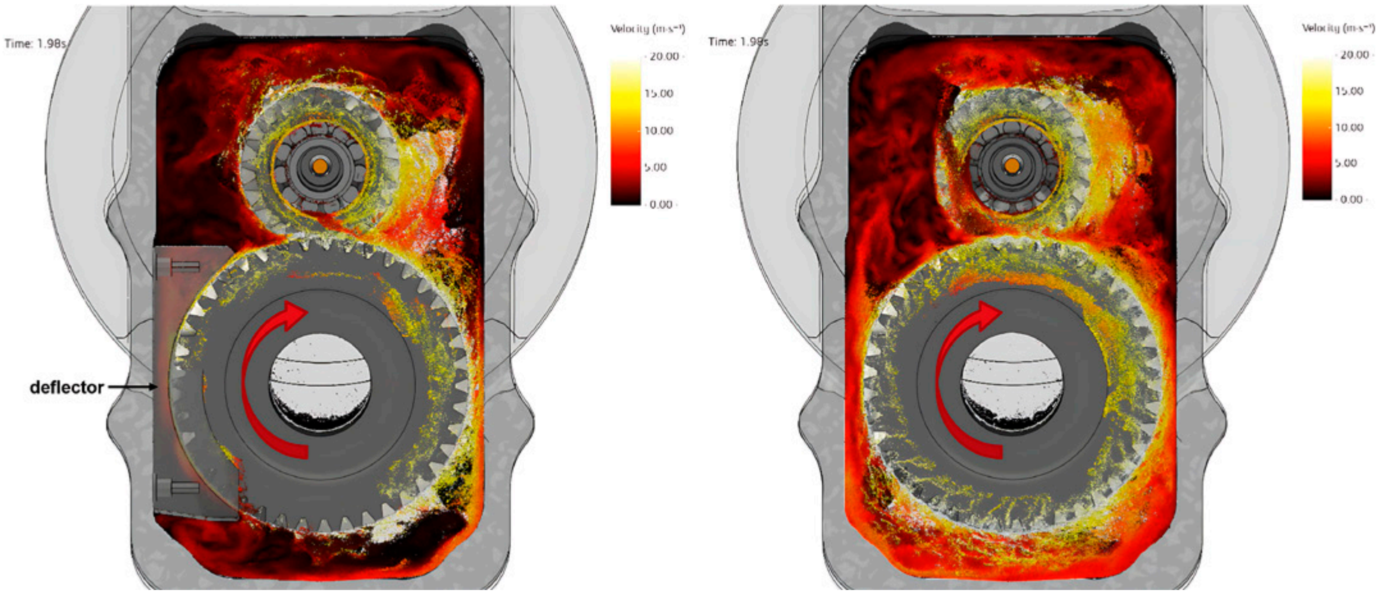


Figure 6—Comparison of the lubricant motion with (left) and without (right) the deflector, showing more movement without the deflector.

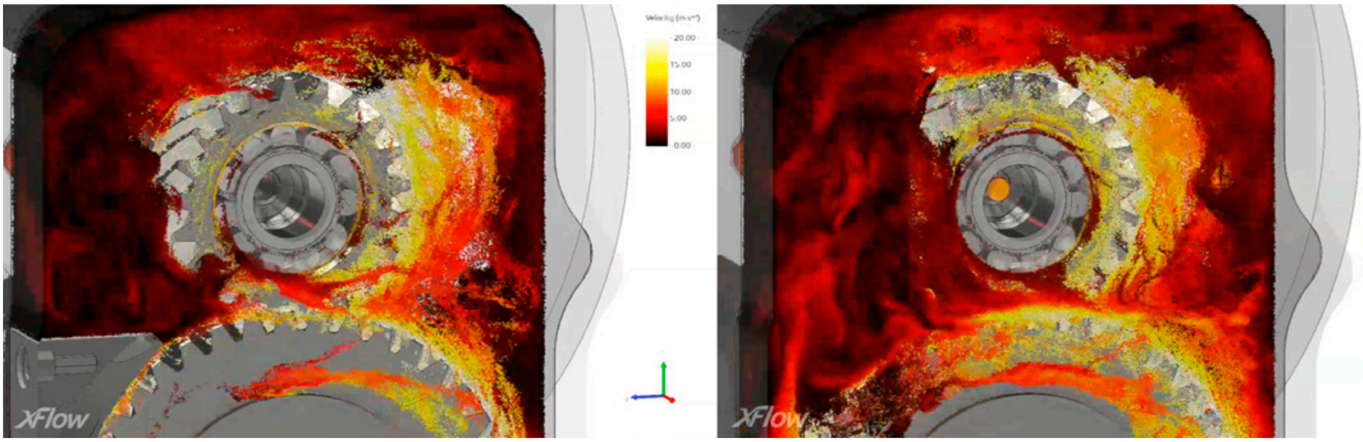


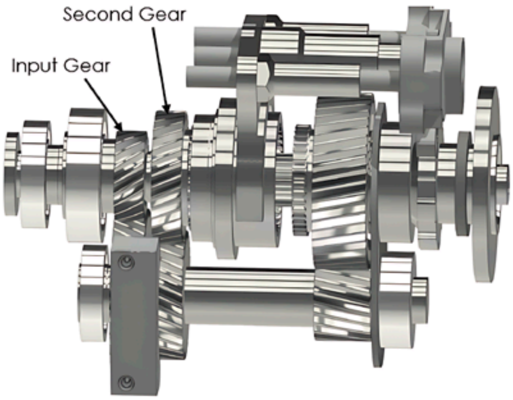
Figure 7—Comparison of the lubricant motion with and without the deflector, zoomed in on the overheating bearing, showing better lubrication without the deflector.

A zoomed-in image in Figure 7 confirms that more lubricant appears to reach the overheating bearing without the deflector. Without the deflector, in the right image, more colored particles are seen in front and around the overheating bearing. Another visual tool can be used to evaluate the cooling efficiency, using the wet areas. They can be displayed by projecting the flow onto solid surfaces. Because the flow is very turbulent, these visuals are challenging to obtain precise information from.

While these observations are qualitative, quantitative data can be extracted to compare the two designs.

Churning losses of all rotating parts provide measurable values to track and compare. Figure 8 reveals a table comparing the measured churning losses on the input and second gear, with and without the deflector. The graph on the right shows the evolution of the churning loss (moment, Mx) with time. After the transition phase that lasts for about 0.5 seconds, the value stabilizes, and an average is computed.

Churning loss [N.m]	Input Gear	Second Gear
With deflector	0.1002	0.1176
No deflector	0.2420	0.7650
ratio x	2.4	6.5



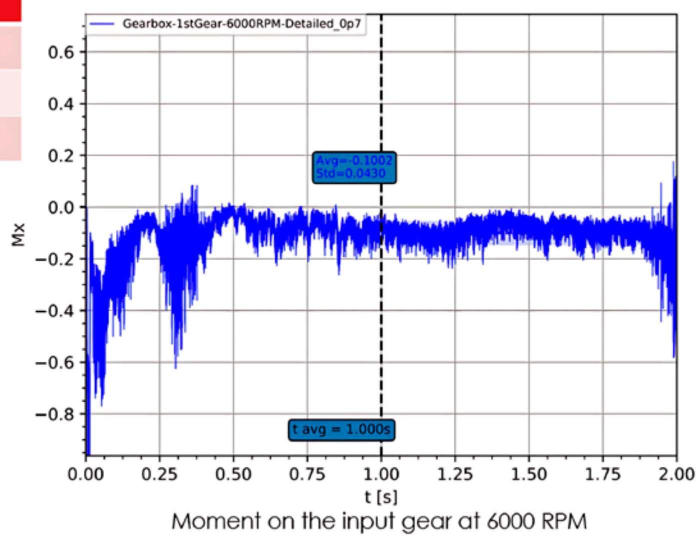


Figure 8—Churning loss estimation of gears showing more important churning losses without the deflector.

Target Cyl.	With deflector	No deflector	Ratio x
Mass Flow [L/min]	11.6	37.7	3.3
VOF [%]	4.5	12.6	2.8

Entry #1	With deflector	No deflector	Ratio x
Mass Flow [L/min]	0.3	1.4	4.7
VOF [%]	4.4	8.7	2.0

4.7x more lubricant enter in the entry #1, on an area 2x larger.

Entry #2	With deflector	No deflector	Ratio x
Mass Flow [L/min]	2.0	4.5	2.2
VOF [%]	15.1	35.3	2.3

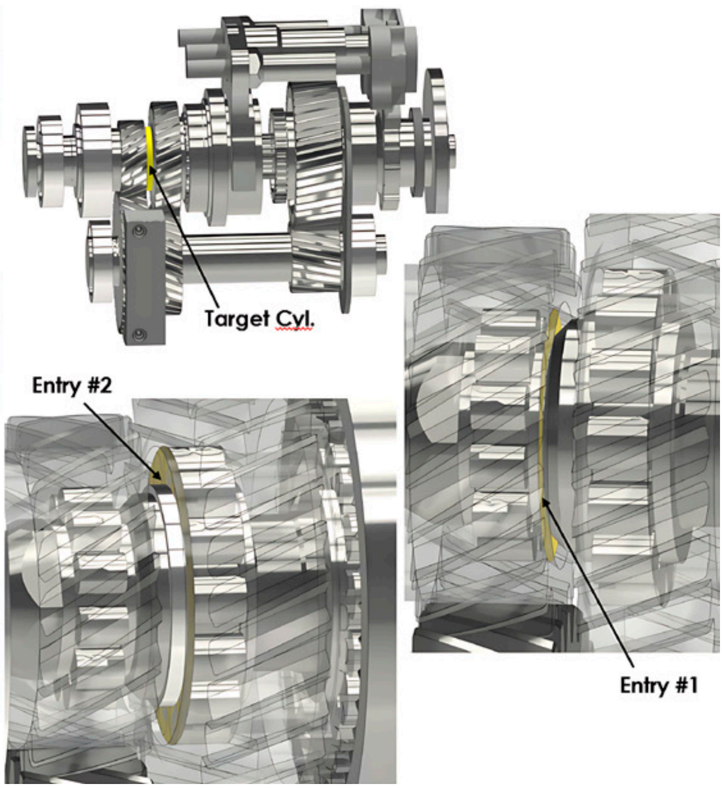


Figure 9—Surface integrals measuring the amount of lubricant in specific areas, indicating that more lubricant enters the narrow region without the deflector.

Churning loss refers to the resistance created by lubricant splashing on a rotating part. Higher churning loss indicates greater lubricant activity. We observed that the churning losses on the input gear are 2.4 times higher without a deflector, and 6.5 times higher on the second gear.

Creating surfaces for post-processing allows the integration of the quantity of lubricant passing through them with time, enabling comparison of the amount reaching specific areas of concern. The distribution of lubricant on these surfaces can also be measured in terms of VOF percentage (volume of fluid). A higher VOF percentage indicates that the lubricant covers a greater area of the surface. In Figure 9, the tables present the quantity of lubricant crossing several surfaces, allowing for comparison with and without a deflector. The Target Cyl refers to the narrow gap between the input gear and the second gear. The Entry #1 refers to the access to the overheating bearing, below the input gear. Entry #2 identifies the access to the roller bearing below the second gear.

Both mass flow and VOF distribution show higher values without the deflector. Through Entry #1, which leads to the overheating bearing, 4.7 times more lubricant flows, indicating that the cooling could be more efficient without the deflector.

The heat transfer coefficients (HTC) are scalar values projected onto all surfaces and can be exported for each part into a text file containing the HTC values and the associated node coordinates (x, y, and z). The user must select a time span during which the flow is fully developed, typically covering at least one rotation of the slowest gear. For each time increment within this period, a text file must be exported. During the heat transfer analysis, the mesh is static, so the node coordinates from the initial increment must also be exported. These initial node coordinates are then associated with the average HTC values at each node, for every part. This process is automated using a Python script. Once the HTC values are processed, they can be imported into the heat transfer analysis to predict the temperatures accurately.

Heat Transfer Scenario Definition

To define the steady-state heat transfer analysis, several parameters need to be set. The thermal conductivity of all materials must be specified. In our project, the casing was made of aluminum while all other parts were made of steel. Thermal contacts between all solid parts must also be defined, as thermal interfaces are never perfect and depend on factors such as surface finish or roughness. We referred to the *Spacecraft Thermal Control Handbook* (Ref. 2) to determine the thermal contact resistance or interface thermal coefficient.

The heat generated by each bearing was defined based on data provided by SKF (Ref. 3), the bearing manufacturer. This data covered 97 load cases for when the first gear is engaged and 43 load cases for the second gear, each representing a specific input gear rotation speed and torque. From these combinations, we selected three worst-case scenarios that generated the most power loss.

Next, the heat transfer coefficients (HTC or film coefficient) at each node were imported to define film conditions that characterize the convective heat exchange, along with an estimated fixed lubricant temperature. Figure 10 illustrates the mapping of the film coefficients on the gears around the narrow region. Given the highly turbulent nature of lubrication inside the casing, assuming a constant temperature throughout is acceptable. The lubricant temperature can be easily adjusted to run multiple scenarios, allowing for the study of its sensitivity on the predicted solid temperatures.

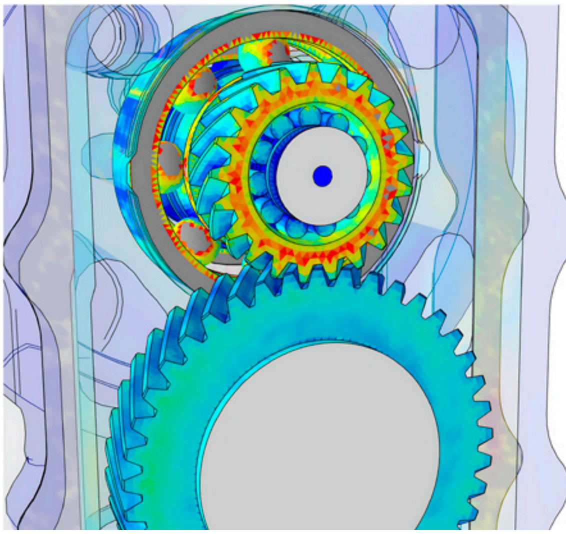


Figure 10—Cut view inside the gearbox showing the convective heat transfer coefficients projected on solid surfaces.

Heat Transfer Post-Processing

The main output is the predicted temperatures of bearings and solids for a particular load case. Figure 11 shows the predicted temperature with the deflector.

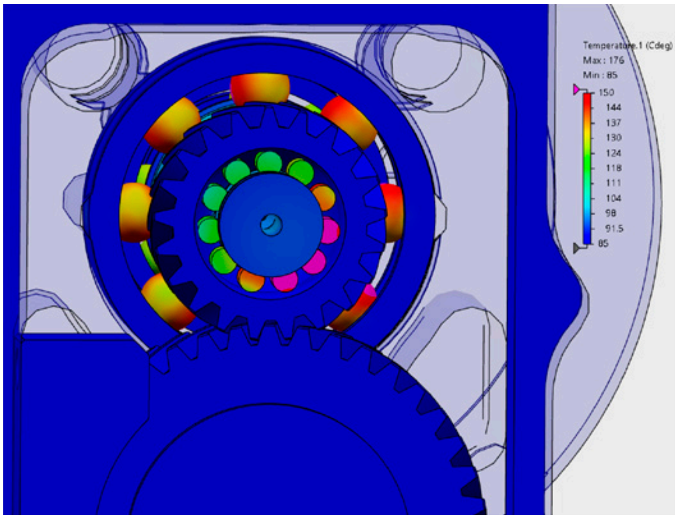


Figure 11—Predicted temperature around the narrow region with the deflector.

In reality, the temperature should be uniform on all bearing rollers due to their high rotational velocity. But considering that the film coefficients are averaged during just one simulated second, to keep calculation cost reasonable, and that the heat transfer analysis is steady state with fixed geometry, a temperature gradient can be observed on the bearing. To remain conservative, the maximum predicted temperature can be used. This misrepresentation of reality is explained by numerical reason, but the interpretation of the results remains acceptable and allows for design comparison and performance evaluation. According to the bearing spec sheet, the bearing could start to accumulate damage above 150°C. The analysis prediction of a maximum bearing temperature of 176°C correlated well with the manufacturer's damage observations on the roller bearing.

Figure 12 reveals the same prediction of temperature without the deflector. It clearly confirms the fact that the lubrication appeared to be better without the deflector, offering better cooling of the overheating bearing.

Ironically, the manufacturer attempted to solve the anticipated overheating problem with the deflector actually exacerbated it.

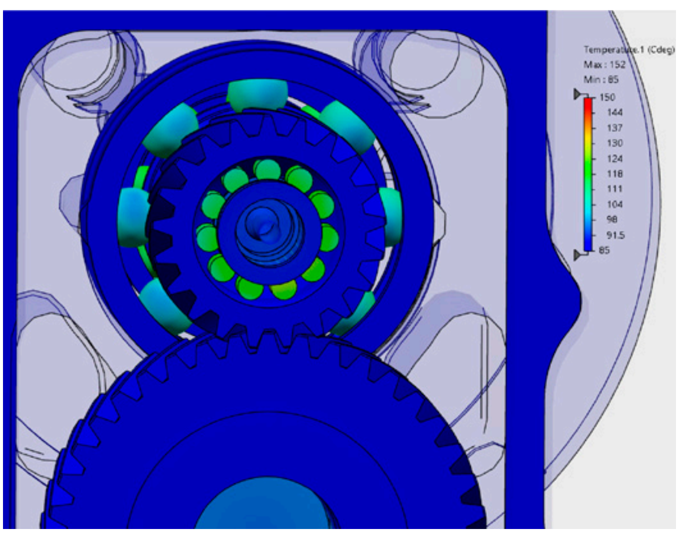


Figure 12—Predicted temperatures without the deflector on and around the problematic bearing.

The steady-state heat transfer analysis completes in a matter of minutes. Running the entire set of load cases is feasible within a few hours of computing time. If the thermal conductivities or thermal resistance values are not well known, these parameters can be quickly and easily varied to study their sensitivity on the predicted temperatures.

Heat flux is another valuable output. Represented by symbols or arrows, it helps the user visualize how heat is being transferred within the gearbox. By focusing on specific surfaces to output the heat flux, the user can evaluate the amount of heat exchanged through solid contact (conduction) and the amount extracted by lubrication (convection).

Correlation with Experimental Data

Correlation of the developed workflow is an essential step to ensure its accuracy and reliability. The process involves several stages, beginning with the visual comparison of lubricant splashing. Slow-motion videos recorded using high-speed cameras are matched with animations generated from the CFD analysis. This visual correlation provides a qualitative assessment of the simulation's accuracy in replicating real-world conditions.

The second stage involves measuring the churning loss of the gearbox. The total torque loss on the test bench includes bearing losses, gear friction, seal friction, and churning losses. Accurate evaluation of the other three components is necessary to isolate and compare the churning losses with the torque measured in the CFD analysis. This quantitative comparison validates the simulation's accuracy in predicting torque losses due to lubricant movement. The solver has been validated based on comparison with experimental data (Ref. 4). Two different scenarios, one single gear and two engaged gears, are tested experimentally and compared with numerical prediction. Figure 13 shows the comparison of experimental versus numerical churning losses estimation using XFlow 2022 solver. It shows a good correlation at various speeds.

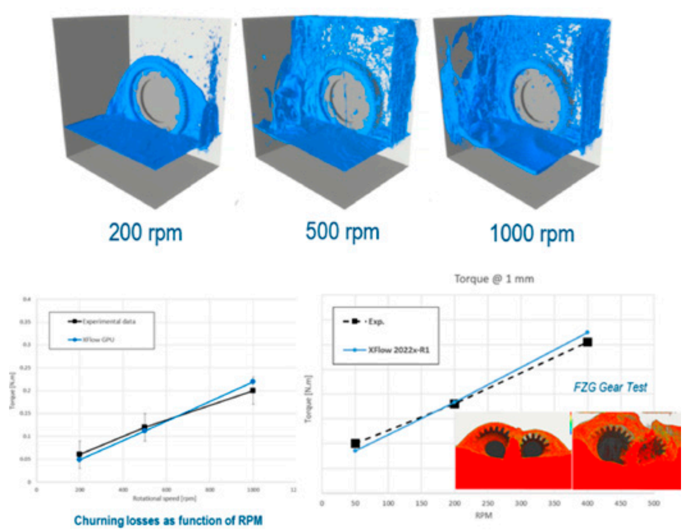


Figure 13—Correlation of churning loss measurements between experiments and numerical predictions (Ref. 4).

Temperature measurements represent the third stage of validation. Temperature data collected on the test bench are compared to the simulated overheating conditions. Ensuring that the CAD model used in simulations accurately represents the prototype on the test bench is critical for this comparison. The same lubricant temperature, applied torque, and rotational speeds must be represented in both physical and simulated environments.

In our project with the gearbox manufacturer, the prototype on the test bench was an earlier version of the design. The test bench lacked a sensor capable of measuring torque losses, which would have allowed us to extract the total churning loss. Additionally, a few temperature labels were installed on shafts that had been altered between the prototype and the CAD model. These labels provided a range of temperatures reached or indicated if the maximum temperature had been exceeded.

The company's team acknowledged that the lubrication animations we provided were comparable to what they had observed through the casing window of their test bench. Our predictive model was able to reproduce the overhearing problem, estimating a temperature of 176°C, above the limit that the bearing can endure without damage.

In many companies, the test team and the CFD analysts work separately. The test team often does not know what information the CFD team needs to correlate their models. Consequently, test reports are frequently incomplete and lack the crucial data required to validate the workflow. Greater collaboration between the test and CFD teams is necessary to build identical prototypes for both the test bench and the simulations. Strategic placement of thermocouples is essential for comparing predicted and actual temperatures, and churning loss measurements should be taken to gain confidence in the accuracy of the simulations.

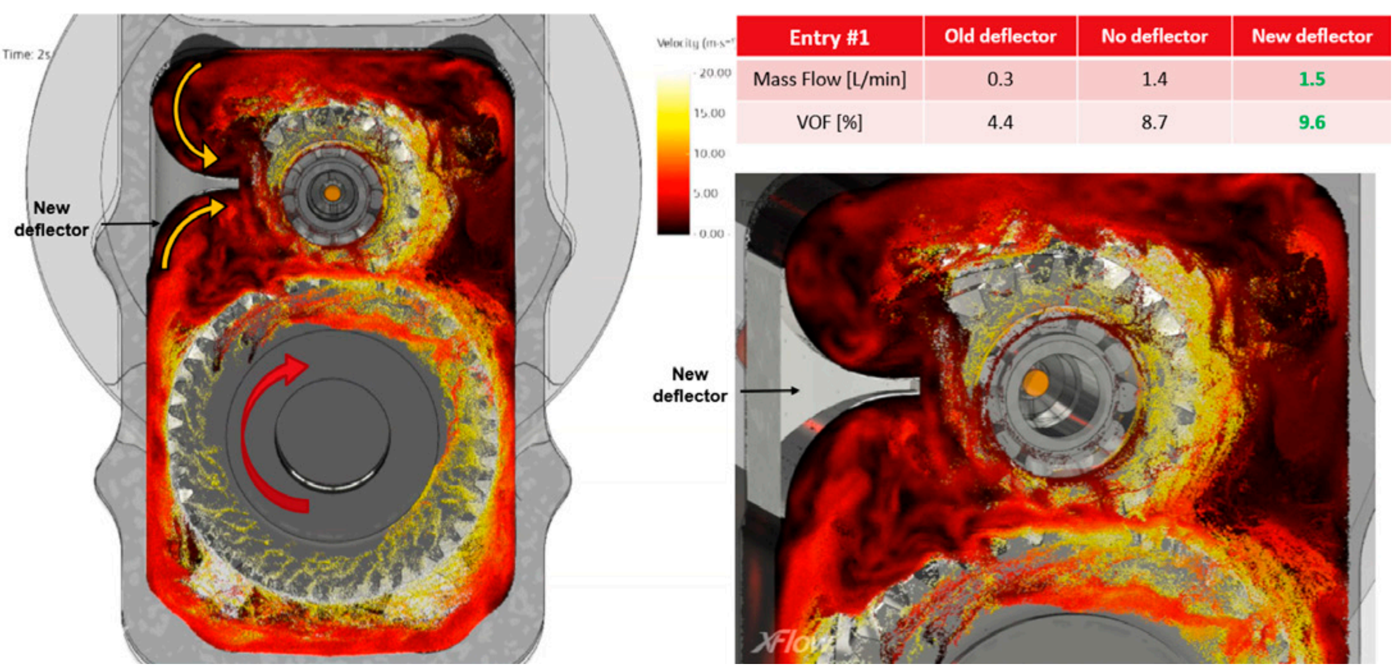
The Power of a Virtual Lab

The developed workflow offers numerous advantages, significantly enhancing the efficiency and accuracy of gearbox lubrication analysis. One of the primary benefits is the quick setup and analysis time. Engineers can prepare an analysis in just a few hours, with post-processing and animation generation automated using scripts. This efficiency allows for rapid iteration and comparison of design variations, enabling engineers to make informed decisions quickly.

Having a numerical model leads to a powerful virtual lab, allowing for the testing of multiple conditions and scenarios without the need for physical prototypes. Engineers can rapidly iterate designs, run designs of experiments (DOE), and find optimized solutions. By adjusting parameters such as gravity equations and initial lubricant levels, various operating conditions can be simulated, including road slopes, acceleration, braking and turning events. Different weather conditions can be modeled by altering lubricant properties, providing a comprehensive understanding of gearbox performance under a wide range of scenarios.

This capability enables the exploration of "what if" scenarios that would be impractical or costly to test experimentally. For instance, simulations can assess the gearbox performance without lubricant, test alternative lubricants, or evaluate the impact of component failures. This flexibility is invaluable for manufacturers, as it enhances their knowledge and expertise, leading to continuous improvement in product design and performance.

In the context of our project, the virtual lab allowed for testing several deflector designs intended to guide more lubricant towards the overheating bearing. The initial deflector design created local lubricant recirculation, which was impossible to detect experimentally. Simulations provided critical insights, revealing the inefficiencies of the initial design and guiding the development of optimized deflector configurations. The improved deflector design, shown in Figure 14, was based on the animations of the lubricant movement. It uses double slopes directing both the flow coming up on the left side wall, and the flow moving counterclockwise around the input gear.



Entry #1	Old deflector	No deflector	New deflector
Mass Flow [L/min]	0.3	1.4	1.5
VOF [%]	4.4	8.7	9.6

Figure 14—Qualitative and quantitative results using the new deflector, showing better lubrication performance compared to the initial deflector design.

No recirculation pattern, nor low velocity areas were observed. Figure 14 shows important lubricant motion near the overheating bearing. The table presents the comparison of flow quantity accessing the overheating bearing, indicating better performance. The improvements compared to without the deflector were not significant, but it shows that virtual testing allows us to quickly evaluate and compare designs.

Quantitative metrics such as churning loss, volume flow across surfaces, and temperatures allow for the ranking of different designs and sensitivity studies. This ranking helps design teams identify the most effective configurations and better understand the parameters that most significantly affect lubrication performance. By providing detailed insights into the lubricant distribution and heat transfer characteristics within the gearbox, the virtual model enables the development of more efficient and reliable designs.

Conclusion

This study has demonstrated the power and practicality of using advanced simulation techniques to tackle real-world engineering problems in gearbox design. By developing a comprehensive analysis workflow that leverages advanced CFD and heat transfer simulations, we successfully reproduced the overheating bearing problem that the manufacturer experienced on their test bench. We evaluated that their deflector design was responsible for flow obstruction, leading to less efficient cooling. Predicting temperatures on the solids, without the deflector, offered the manufacturer a quick solution to overcome the overheating problem. And by studying the lubricant motion from the analyses, we proposed a double-slope deflector that could improve the lubrication efficiency.

The virtual model approach offers a game-changing solution for gearbox manufacturers. By reducing the time and cost associated with physical prototyping, companies can quickly iterate on their designs, identifying and resolving flaws before they become costly issues. This workflow, which runs efficiently on GPU-powered systems, allows manufacturers to simulate complex lubrication dynamics and thermal interactions with remarkable accuracy and speed.

With this capability, manufacturers can explore a wide range of operating conditions, including extreme scenarios, to ensure their gearboxes perform reliably under all circumstances. The detailed insights gained from these simulations enable the development of optimized, high-performance designs that meet the market demand and become more competitive.

Furthermore, the integration of simulation and experimental validation fosters better collaboration between engineering teams, ensuring that the models used are both accurate and reliable. This synergy not only improves the design process but also builds confidence in the final product.

In summary, the adoption of this advanced workflow empowers gearbox manufacturers to innovate faster and more cost-effectively. By embracing numerical analyses and virtual labs, companies can enhance their product development cycles, leading to superior gearboxes that deliver improved efficiency, reliability, and longevity. This approach represents a significant advancement in engineering capabilities, positioning businesses to stay ahead in a competitive market.

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