15th IFK
Proc. of the 15th International Fluid Power Conference <Symposium/Conference>
<DOI>

Navigating Electrification Challenges: Low Speed Behavior of External Gear Pumps

Nandakumar P S[1], Vishnudas Ramaswamy[1], Stefan Kock[2], Martin Laube[3]

[1]Bosch Rexroth India, Advanced Engineering External Gear Units, Bengaluru, India

[2]Bosch Rexroth AG, Advanced Engineering External Gear Units, Nürnberg, Germany

[3]Bosch Rexroth AG, Head of Product Area External Gear Units, Lohr a. Main, Germany

E-Mail: npa4ban@bosch.com, Ramaswamy.Vishnudas@boschrexroth.co.in, stefan.kock@boschrexroth.de, martin.laube@boschrexroth.de,

Abstract.

Electrification in mobile hydraulics, particularly for material handling applications like electric forklifts, demands external gear pumps capable of reliable operation at very low speeds, high pressures, and elevated temperatures. The low-speed requirement arises from the low-flow needs of the hydraulic system. However, the operational speeds required by material handling applications often fall below the current minimum speed limit for external gear pumps (typically 500 rpm). This can lead to insufficient lubrication of tribological contacts, excessive wear of pump components (e.g.: bearings and gears), and significant volumetric losses. Bosch Rexroth has addressed these low-speed challenges in external gear pumps through the development of specialized low-speed characterization parameters and ongoing research into various pump optimization methodologies. This paper is a comprehensive compilation of low-speed operation requirements and challenges (e.g.: volumetric losses and wear), low-speed pump performance characterization parameters available with Bosch Rexroth, and ongoing research to address low-speed challenges (e.g.: surface coating technology). The paper introduces and explains two parameters to characterize the low-speed behaviour of external gear pumps: “zero delivery speed” and “hydrodynamic speed limit”. Zero delivery speed defines the minimum operating speed of the pump at which the theoretical flow equals volumetric losses. Hydrodynamic speed limit describes the operating speed of the pump corresponding to lubrication regime change from mixed film lubrication regime to hydrodynamic lubrication regime.

The research topics explored in this paper offer practical solutions to optimize external gear pumps for low-speed operation in mobile machinery. These studies directly address the wear on bearing and gear faces, and volumetric loss associated with low-speed operation of external gear pumps.

Keywords. Electrification, External gear pump, Low-speed, Mobile machinery

1. INTRODUCTION

Bosch Rexroth is one of the world's leading suppliers of drive and control technologies, significantly impacting the development in the industrial hydraulics sector. The company's core focus areas span mobile and industrial applications, factory automation, and digitization and software development, providing comprehensive solutions that integrate electric drives and valves, linear motion technologies, and hydraulics. Bosch Rexroth's extensive product portfolio encompasses hydraulic pumps, motors, valves, cylinders, and power units, catering to diverse industrial and mobile machinery requirements.

Hydraulic systems are integral part of mobile machinery deployed in agriculture, material handling, construction, and mining, to convert energy into fluid power and then into mechanical energy, enabling various actuators to produce force or motion. A typical hydraulic system comprises of a power source (e.g.: batteries), drive (e.g.: servo motors), pump, control elements (e.g.: valves), actuators (e.g.: cylinders, hydro motors), auxiliary components (e.g.: filters, accumulators), and a working medium (e.g.: hydraulic oil). A hydraulic system can either have a mechanical-hydraulic drive system where an internal combustion engine is used to drive the pump, or an electric-hydraulic drive system where an electric motor is used to drive the pump. Hydraulic systems are currently undergoing transformational change towards electrification where an electric-hydraulic drive system replaces the conventional mechanical-hydraulic drive system, which ensures improved energy utilization and reduced air and noise pollution. This is primarily driven by the electrification trends in non-road mobile machineries [1]. The material handling sector is in the forefront of electrification and has undergone much electrification in last decade, especially smaller forklifts, and the trend is continuing to bigger forklifts and reach trucks.

Applications such as lifting at very low speeds or idle machine operation require hydraulic systems capable of generating low flow rates while keeping the working pressure on the desired level. Electric-hydraulic drive systems, which utilize electric motors, can operate effectively at low speeds [2] compared to internal combustion engines. To manage low-flow criteria, traditional valve control systems are often implemented. These systems deploy additional valves to regulate flow, but this approach increases system complexity and cost. Furthermore, the energy losses associated with these valves significantly reduce the overall hydraulic system efficiency [3].

An alternative is a pump-controlled system that employs a pump capable of operating efficiently at low speeds, thereby eliminating the need for additional valves. External gear pumps (EGPs) are widely used in hydraulic systems due to their low cost, and simple and compact design. However, continuous operation of EGPs for electric-hydraulic drive systems under low-speed conditions implies significant challenges, including operating points with reduced volumetric efficiency and wear of components due to inadequate lubrication.

The objective of this paper is to:

1. Present the challenges and requirements from low-speed mobile machinery applications emerging due to electrification of hydraulic systems.
2. Evaluate the current capabilities of Rexroth EGPs under low-speed conditions to highlight the challenges.

3. Elaborate potential design optimizations to meet future market requirements in the electrified mobile machinery sector.

This paper compiles a set of operational requirements for EGPs operating at low speeds, specifically derived from mobile material handling applications. The work then investigates the low-speed performance of these pumps. To evaluate the minimum operational speed limit and to identify the lubrication regime corresponding to operating conditions, two parameters will be described– "zero delivery speed" and "hydrodynamic speed limit". Variations of these results with operating conditions (e.g.: speed, pressure, and temperature) are presented to illustrate the application of these parameters in low-speed performance analysis. Subsequently, the key challenges inherent in low-speed EGPs operation and their potential causes are identified. Finally, this paper consolidates relevant research addressing these challenges.

The paper concludes by synthesizing the findings and identifying directions for future research. By providing a comprehensive analysis of low-speed behaviour and presenting concrete optimization strategies, this paper aims to promote the broader adoption of EGPs in a wider range of electrification applications, thus paving the way for more efficient and reliable solutions.

2. External gear pumps and low-speed operation: Status quo

The previous section introduced the integration of EGPs into electric-hydraulic drive systems. This section will delve deeper into EGPs, exploring the applications, the challenges, and the specific requirements for their operation under low-speed conditions.

2.1. External gear pumps

EGPs are positive rotary-displacement pumps. Meshing of drive and driven gears creates a low-pressure region at the suction side to which working fluid enters and is carried along with gear teeth and squeezed out at the outlet side. **Figure 1(b)** is the exploded view of an EGP with the major components highlighted. Two pairs of bearing and sleeve, housing, drive and driven gear, and covers constitute an EGP. EGPs stand out for their:

- Simple, robust and compact design.
- High volumetric efficiency and power density.
- Broad operational speed capabilities (500-6000 rotations per minute (rpm)) depending on pump size and pressure (0-280 bar).
- Low cost and maintenance.

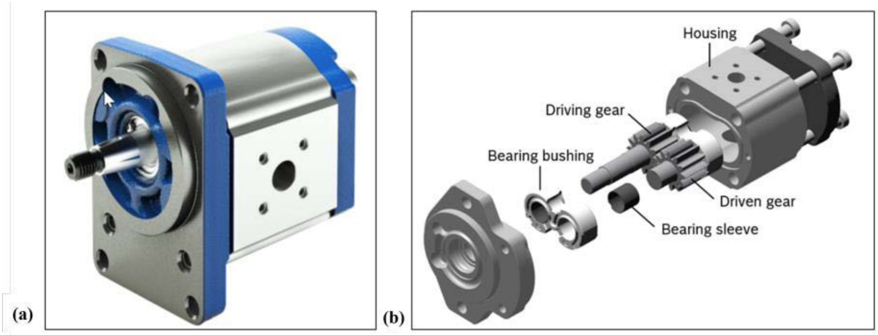

Figure 1: (a) Picture of a Rexroth external gear pump, (b) external gear pump components

Rexroth EGPs are widely used across diverse applications, particularly due to the low-noise operation achieved through their Silence and Silence Plus technologies, even under high-pressure conditions. While these pumps typically operate across a broad speed range, from 500-6000 rpm (for 1 cubic centimetre (ccm) pumps), many mobile and industrial applications specifically utilize pumps with displacements ranging from 7-28 ccm, where the operational speed range is often constrained to 500-4000 rpm. Anything below 500 rpm is treated as a low-speed requirement. The next section evaluates the general low-speed requirements from electrified mobile machinery applications.

2.2. Low-speed operation of external gear pumps: Application, Requirements, and Challenges

The demand for low-rotational-speed pumps is prominent in electrified material handling applications, which includes reach trucks, forklifts, scissor lifts, mobile cranes etc. **Figure 2** depicts a general speed-load diagram (or duty cycle) for EGPs in material handling application, where a significant portion of EGPs operation occurs at 100-300 rpm for short durations, even with intermittent pressures up to 280 bar. All these requirements exist within a demanding product lifecycle of 20000 operating hours for the pump. Apart from the mentioned conditions, it is well documented that the start-stop operations of the system pose significant threat to mechanical components like bearings [4]. EGPs have the capability to meet these requirements for short durations or limited load cycles, but continuous operation under low-speed conditions is to be investigated. The combination of low speed (below 500 rpm), high pressure (above 250 bar), and long and continuous operation (20000 operating hours) defines emerging low-speed requirements in the electric forklift market. These low speeds are crucial for tasks like exact positioning of loads, stacking, and automated movements, highlighting the need for highly precise movement and fine control of the forks. But most EGPs are not designed for continuous operation under such load collectives in the electrified forklift market; this is where active research is required.

Beyond material handling, the necessity for low rotational speed extends to applications like agriculture and construction demanding precise movements and control of actuators. Agricultural machinery requires precise planting and harvesting, where forward speed must be matched to implement function and ground conditions. Furthermore, road construction equipment exemplifies this requirement, as paving and compacting demand consistent, low forward speeds for optimal material laydown and compaction density, effectively requiring machines to "crawl."

Figure 2 highlights the need for both low rotational speed operation and high rotational speed operation, under varying pressures, which are prevalent in material handling and agriculture applications that typically utilize fixed displacement pumps. Other pumps most used in mobile machinery applications include internal gear pumps and axial piston pumps. While internal gear pumps demonstrate comparable performance at lower speeds [5], EGPs surpass them in high-speed operation. Axial piston pumps, though capable, are generally costly and noisy to serve as a viable alternative to EGPs. Furthermore, axial piston pumps are more susceptible to oil contamination, posing an additional challenge compared to the more robust EGPs. Among the available options, EGPs emerge as the most suitable choice for the applications that require both low-speed and high-speed capabilities, specifically due to their cost effectiveness and simple construction.

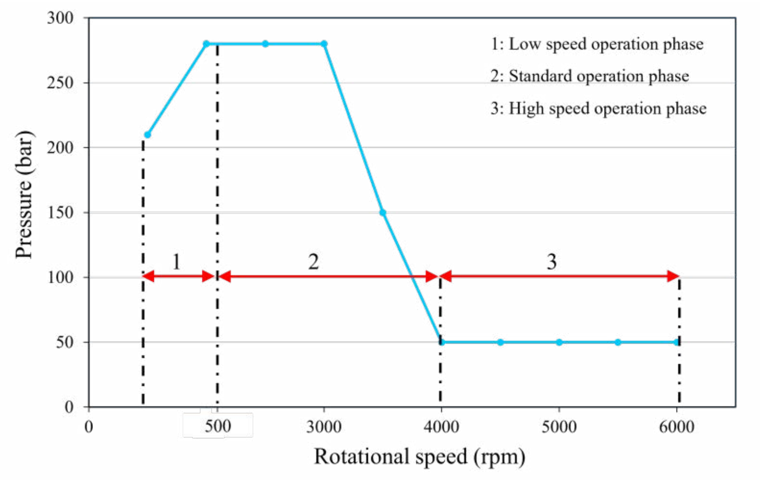

Figure 2: Example of a specific speed-load diagram for external gear pumps in material handling application

In short, EGPs have considerable potential to meet new requirements from mobile machinery application. Electrification of mobile machinery require pumps with both low-speed and high-speed capability. Pumps are expected to operate continuously under low-speed and high-pressure conditions. This brings new challenges and opportunities for external gear pump. This opens the possibility and requirement to study and optimize the low-speed behaviour of EGPs.

3. Low-speed operation: Challenges

The preceding section focused on EGPs, and requirements for low-speed operation. The subsequent paragraphs will detail the specific challenges that arise during low-speed operation. Two major challenges are identified through literature review, field experience, and pump tests: volumetric losses inside the pump and wear of the pump components.

3.1. Volumetric losses

Volumetric losses describe the flow loss from the pump through internal leakage paths. Major internal leakage paths include the gap between housing and gear teeth tip, through gear flank contact region, between bearing face and gear face and between bearing contact faces. Internal leakage paths reduce the pump's net flow rate, thereby decreasing volumetric efficiency. Higher volumetric loss limits the minimum operating speed of the pump as the theoretical flow rate of the pump will equal the volumetric loss of the pump.

3.2. Wear of components

It is a fundamental principle that the flow rate from an EGPs is directly proportional to its operating speed. Consequently, at very low speeds, the resulting flow rate is significantly reduced. Low flow rate affects the lubrication and cooling of pump components. Apart from low flow rate, the hydrodynamic force generated by the rotation of the shaft is not sufficient to ensure a hydrodynamic lubrication regime between tribological contacts (explained in next section). During low-speed operation, the pump will be operating in mixed film lubrication regime which accelerates the wear of components. Along with lubrication, the pump working medium (oil) carries the chips generated due to the surface contacts inside the pump and prevents further wear or crack formation in pump components. Consequently, low flow rate leads to component wear, with bearings and gears being particularly susceptible. Abrasive and adhesive wear are a well-documented tribological phenomenon [6], which significantly diminishes the endurance life of these components and of the pump. Especially, continuous operation under low-speed conditions has been observed to cause partial removal of the polymer layer from polymer sleeves.

Apart from volumetric losses and wear, low flow rate leads to an elevated local pump temperature (i.e., the temperature of the working fluid inside the pump) as the cooling rate is directly proportional to flow rate. This elevated temperature further reduces the working fluid's viscosity or can cause permanent damage, such as oil degradation [7] thereby intensifying the lubrication deficiency. This creates a destructive cycle that continues until noticeable damage to the pump occurs.

In conclusion, most challenges observed during the low-speed operation of EGPs are due to volumetric losses, and wear of the components.

4. VOLUMETRIC LOSS: EVALUATION AND CHARACTERIZATION METHODOLOGY

The preceding section underscores challenges during low-speed operation and the need to investigate volumetric loss of the pump. Addressing these requirements requires testing capabilities and matured evaluation methodologies. The following section explains:

- Testing capability to measure and calculate flow rate and volumetric losses (Volumetric performance investigation test)
- Evaluation of low-speed performance (Volumetric loss characterization, zero delivery speed (hereafter ZDS))

Volumetric efficiency (η_{Vol}) describes the capability of the pump to deliver a flow rate close to its theoretical displacement, indicating the quantity of internal fluid leakage (Q_l in litre per minute (lpm)). Volumetric efficiency is calculated from the theoretical flow rate (Q_{th}, in lpm) and real or measured flow rate (Q_{real}, in lpm). The measured flow rate is the flow rate generated by the EGPs during the operation. Theoretical flow rate is calculated from rotational speed (n, in rpm) and theoretical flow (V_{th}, in litre per revolution) as:

$$Q_{th} = n \times V_{th} \qquad (4.1.1)$$

Volumetric efficiency (η_{Vol}) is calculated as:

$$\eta_{Vol} = \frac{Q_{real}}{Q_{th}} \times 100\ \% \ = \left(1 - \frac{Q_l}{Q_{th}}\right) \times\ 100\ \% \qquad (4.1.2)$$

Volumetric losses reduce the real flow rate of an EGPs, leading to elevated temperatures and reducing the flow available for operating the working hydraulic components like hydraulic cylinders. These losses are approximately independent of rotational speed but highly dependent on operating pressure [8]. At low-speed operation, the real flow rate from the pump is inherently small and volumetric losses further diminish the performance of the pump. Therefore, accurately monitoring and characterizing a pump's volumetric losses is crucial for understanding its low-speed behaviour, necessitating mature testing and characterization methodologies.

4.1. Volumetric loss: Testing facility

Test benches capable for the measurement and recording of operating speed, operating pressure, flow rate, torque loss, and suction and outlet temperature are used to calculate results including volumetric efficiency, and volumetric losses. The same test benches are used to derive ZDS and hydrodynamic speed limit (hereafter HSL). The test bench includes a servo motor (e.g.: 45 kW for 16 ccm pump), a coupler to attach pump with motor, flow meter, rotational speed sensor, suction and outlet temperature sensor, pressure relief valve and an external leakage sensor. The test benches can test pumps from wide range of sizes (e.g.: 1 ccm to 45 ccm), wide range of pressure (e.g.: 0 to 300 bar) and temperature (e.g.: 100 °C). Testing is conducted on different batches and different number of pumps to ensure statistical confidence.

4.2. Volumetric loss characterization: Variation with pressure and temperature

Volumetric losses, flow rate, and volumetric efficiency are derived from the test bench data. **Figure 3(a-c)** presents the volumetric losses, flow rate and volumetric efficiency characteristics for different temperatures and pressures (P), keeping the operational speed constant. From **Figure 3(a)** it is observed that the maximum volumetric loss occurs in the medium pressure range. It is expected that volumetric loss of an EGPs will increase with increase in pressure, because of the higher-pressure gradient between suction and pressure side. However, the volumetric losses reduce from medium pressure to high pressure. This is primarily due to the process of "run-in", which every pump undergoes during initial operation. Run-in is the process of deepening the leakage path between gear teeth tip and housing wall during the initial operation of the pump in high pressure condition. Run-in occurs due to the bending and misalignment of gears (towards suction side) at high pressure operation. This causes excessive material removal from the suction side housing wall, and closing the leakage path for selected "run-in" pressure (usually 10% above the maximum operating pressure). For operation under lower pressures of the pump, volumetric efficiency will be reduced due to the enlarged leakage path. However, as the gear starts to bend or misalign towards suction side due to higher pressure, the leakage path created by run in process is being closed and this phenomenon enhances the volumetric efficiency. The closing of above-mentioned leakage gap happens only for “Run-in” pressure. As a drawback, the flow and volumetric efficiency will be maximum only at run-in pressure compared to other pressure conditions. This is the reason for smaller volumetric efficiency and higher volumetric losses at mid-pressure range. The closure of run-in track due to high pressure is called passive radial gap compensation.

Figure 3(a) also shows the impact of temperature on volumetric losses. Comparing the results for 50 °C and 80 °C, a significant increase in volumetric loss is observed with increase in temperature. The maximum volumetric loss at 80 °C is more than twice that at 50 °C. As temperature increases, viscosity of oil decreases and reduction in viscosity leads to higher volumetric losses.

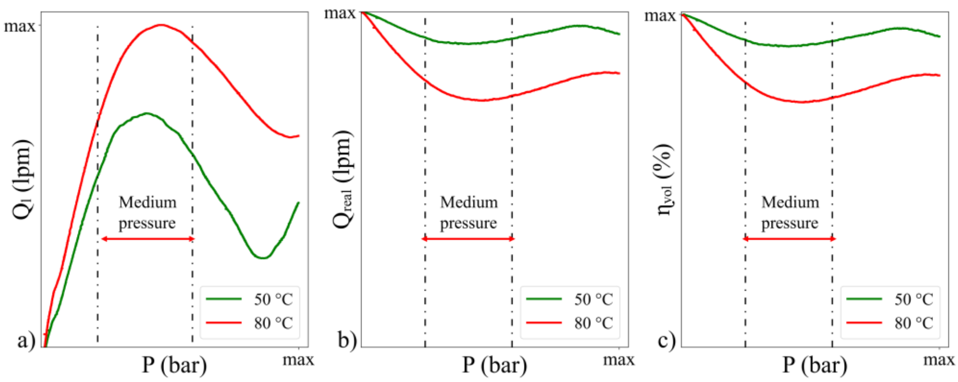

Figure 3: Variation of (a) volumetric flow loss, (b) flow rate, and (c) volumetric efficiency with pressure and temperature

Figure 3(b) and Figure 3(c) discusses the flow rate variation and volumetric efficiency variation with temperature and pressure. Flow rate and volumetric efficiency attains a minimum value at medium pressure range and maximum is observed during low- and high-pressure operation. With respect to temperature, a considerable drop observed at elevated temperature cases. The findings are aligned with volumetric loss findings as volumetric losses are maximum at medium pressure cases and minimum at low- and high-pressure cases, and volumetric loss increases with temperature. The observed results clearly indicate that medium pressure and high temperatures are the critical operating conditions for EGPs. These behaviours are valid for all modern external gear units using passive radial gap compensation over “run-in track”.

4.3. Definition and calculation of zero delivery speed (ZDS)

Volumetric loss is important as it restricts the minimum operational speed of the pump. Understanding the minimum possible speed by the EGPs is required to define the operating boundary conditions. In this context, ZDS is the rotational speed at which the pump is operating without any measurable flow for a defined pressure and temperature. ZDS helps to identify the lower speed boundary for an EGP. Below ZDS, the volumetric losses from the pump equals flow from the pump and hence the pump is unable to produce any measurable flow at the outlet.

The calculation of ZDS for a given temperature and pressure, is derived from the flow rate - speed curve, for a fixed pressure and temperature condition as depicted in **Figure 4**. The speed (x-axis) corresponding to zero flow (y-axis) is calculated from the experimental data. The intercept point represents the state of no flow though the rotational speed of the pump is not zero.

ZDS is proportional to the flow capabilities of the pump. A pump with higher outlet flow (or with low volumetric losses) can provide flow at lower speeds. Flow rate and thereby ZDS is influenced by both operating temperature and pressure.

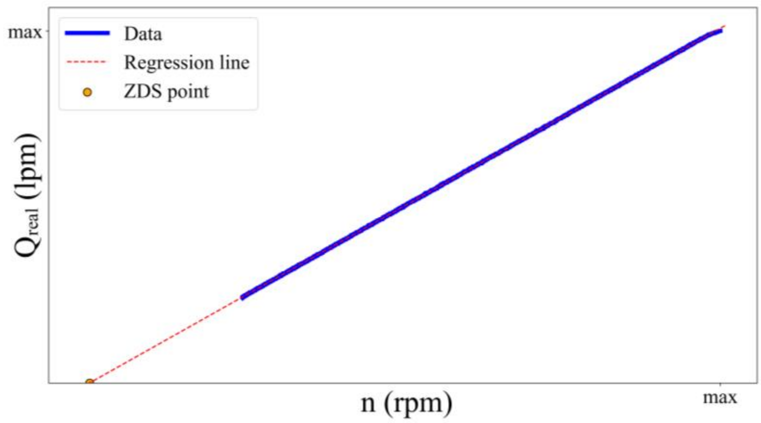

Figure 4: Calculation zero delivery speed from the flow versus speed curve

Figure 5 presents the ZDS variation with pressure for two temperature cases. As depicted in **Figure 5**, the variation of ZDS with pressure exhibits a parabolic profile, with its peak observed in the "medium pressure" or "centre pressure" range. This behaviour is consistent with the pump volumetric efficiency, flow rate, and volumetric loss characteristics, as shown in **Figure 3(a-c)**. The influence of temperature on ZDS is also presented in **Figure 5**. An increase in operating temperature leads to a reduction in flow rate, consequently elevating the ZDS. **Figure 5** conveys that at medium pressure and high temperature cases, pump should be run at higher speeds to have flow from the pump.

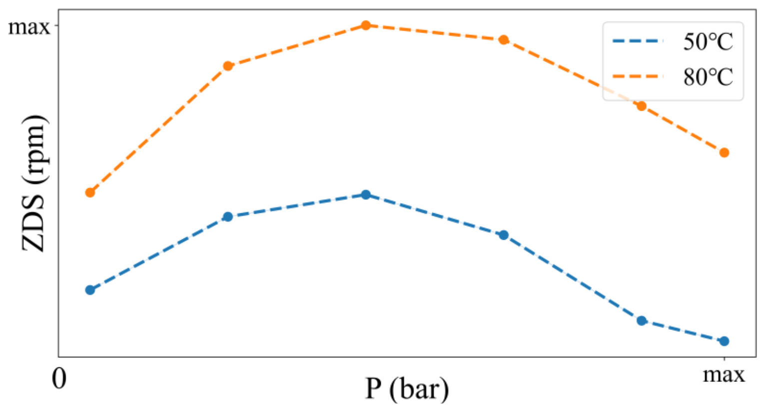

Figure 5: Variation of zero delivery speed with pressure and temperature

5. WEAR: EVALUATION AND CHARACTERIZATION METHODOLOGY

Apart from volumetric losses, wear is identified as a challenge during low-speed operation. The following section details about the characterization and evaluation methodology for wear.

Major tribological contacts of a pump include that between housing and gears, gears and bearings and between shaft and sleeve. During operation, the pump components and these tribological contacts are immersed in working oil which acts as the lubrication medium. Depending on the operating parameters like rotational speed, pressure, oil viscosity and temperature, a pump could be operating under boundary lubrication regime, mixed lubrication regime, or hydrodynamic lubrication regime. Hydrodynamic lubrication regime is characterized by a thick lubrication oil film between tribological contacts and ensures minimum contact wear during operation, while mixed film lubrication regime is characterized by thin film lubrication oil film, and metal to polymer contact between tribological contacts. Components operating under mixed film lubrication could encounter high wear and lubrication issues. The transition from mixed film lubrication to hydrodynamic lubrication is identified as the transition speed point, and adapted Stribeck curve is used to identify the transition point and lubrication regime [9]. Stribeck curve is usually deployed for bearing lubrication regime identification, but the concept is, under simplification and assumptions, applicable to pumps even though a pump consists of multiple tribological contacts including gear and bearings. The Stribeck curve for a pump discusses about the overall torque loss from the pump, which includes torque loss through all the tribological contact and viscos loss due to working oil. Transition speed from the Stribeck curve describes the minimum torque loss point for the pump, it doesn't mean all the components of the pump will be working in the hydrodynamic lubrication regime if the operating speed is above transition speed. At low-speed operating conditions, the pump speed could be below the transition speed point, and this will induce wear of the components and eventual failure of the pump. The load cycle capability of the pump for continuous operation under low-speed is restricted by the mixed film lubrication regime and the wear associated with the lubrication regime.

Above sections detailed about the importance of transition speed point and wear associated with mixed film lubrication regime. Extracting transition speed point from the Stribeck curve for the pump presents practical challenges. To address this, the paper is proposing a model that simplified the Stribeck curve into a function of torque loss and rotational speed by fixing operating pressure and temperature. The transition speed between mixed film lubrication regime and hydrodynamic lubrication regime is identified from this curve. This speed is defined as HSL. **Figure 6** represent a simplified Stribeck curve with lubrication regime and HSL illustrated.

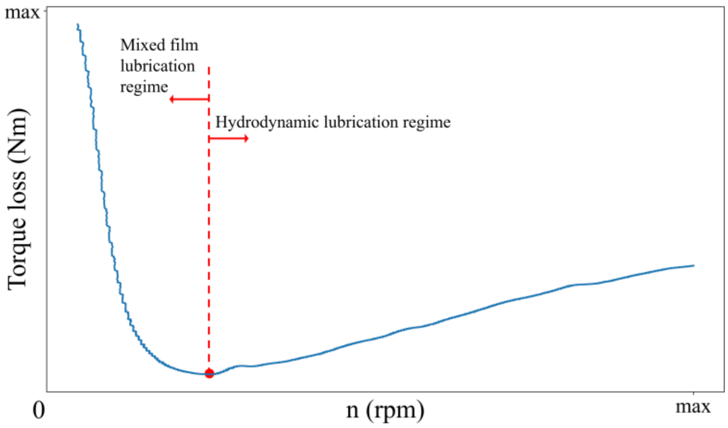

Figure 6: A simplified version of Stribeck curve with lubrication regime distinguished

5.1. Definition and calculation of hydrodynamic speed limit (HSL)

HSL is a parameter to determine the speed corresponding to minimum torque loss. Minimum torque loss directly correlates to minimum coefficient of friction (friction due to surface contact and viscosity of oil) and thereby to the speed at which the wear is minimum. Hypothetically pumps operating above the HSL could be under hydrodynamic lubrication regime and have better durability life in the long run. However further research is required to evaluate this hypothesis. It is possible that the pump components will be operating under different lubrication regimes even though the overall torque loss from the pump is corresponding to hydrodynamic lubrication. **Figure 7** shows a simplified Stribeck curve for EGPs. **Figure 7** illustrates HSL value for different pressure cases. **Figure 7** show a steep increase in torque loss value as operating speed falls below HSL. Continuous operation of pump under mixed lubrication regime will significantly affect the pump durability life, and for continuous operation, HSL is the minimum speed condition for the pump.

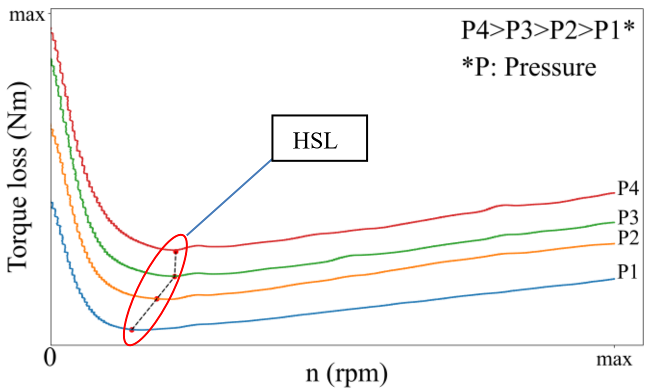

Figure 7: Torque loss versus speed curve for different pressures

HSL is a function of the operating pressure, temperature and viscosity of working medium. **Figure 8** presents the variation of HSL with pressure for a different temperature case. As the pressure increases, the hydrodynamic force required to generate an oil film between the components also increases. The shaft rotation speed and hydrodynamic force generated are proportional. At higher pressure cases, higher hydrodynamic force is required to ensure hydrodynamic lubrication and operating speed is required to generate this force. Hence the HSL increases with pressure.

Figure 8 illustrates impact of temperature on HSL. An increase in operating temperature leads to a reduction in fluid viscosity, consequently reducing the generated hydrodynamic force and thus elevating the HSL required for hydrodynamic lubrication.

The last two sections described the various low-speed characterization parameters available including testing capabilities. It is observed that the ZDS and HSL ranges from 400 to 750 rpm (for 14 ccm external gear pump with passive radial gap compensation). However, the low-speed applications demand operational speed to be below 400 rpm. The decision if the pump is suitable for low-speed operation condition need to be evaluated carefully by considering the requirements and results from parameters like ZDS and HSL.

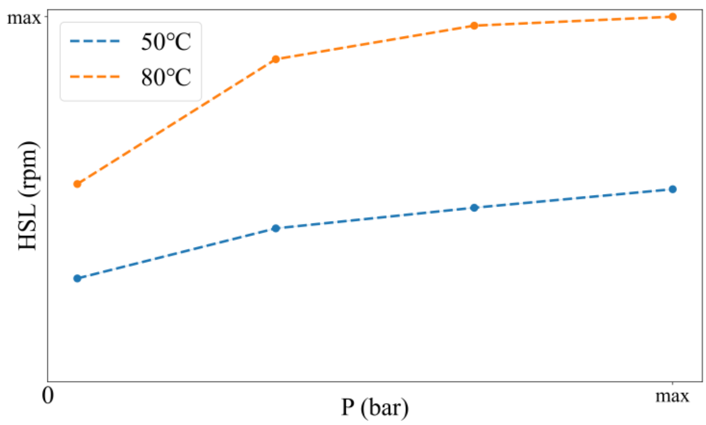

Figure 8: Variation of hydrodynamic speed limit with pressure and temperature

To study the wear performance and durability life of pump and components under low-speed operation, specific tests with focus on continuous operation of the pump and its components are developed. These tests are described in the pump durability testing section.

5.2. Wear measurement: Pump durability test

Pump durability tests are used to study the performance of the pump during and after continuous operation. These tests help to evaluate the wear on components, and variation in performance of the pump with continuous operation. Depending on the study requirements, a loading cycle is formulated for every test. This loading cycle will be executed for long periods of time (e.g.: 1000 hour) after which the pump will undergo through evaluation including performance, and tribological assessments. Tests are completed using a volumetric performance investigation test bench. Pressure, flow, external leakage and torque are continuously monitored and recorded for further analysis.

All the pumps that undergo durability test need to be investigated for their tribological parameters, including measurement of wear and microstructural analysis.

6. LOW-SPEED OPERATION: OPTIMIZATION MEASURES

Advanced research into the low-speed performance of EGPs is ongoing at scientific communities. These research addresses two critical issues: optimizing the pump to reduce volumetric losses, and enhance the wear robustness and reduce friction between components. The subsequent paragraphs detail some of the key research initiatives.

6.1. Pump optimization measures to reduce volumetric losses

High volumetric losses directly contribute to high ZDS for a pump. This limits the minimum operating speed for the pump and forces the pump to operate at higher rotational speeds. Following section compiles the research on this.

6.1.1. Precise bearing technology

Polytetrafluoroethylene (PTFE) based metal-polymer sleeves currently represent the state-of-the-art for radial bearings in EGPs. However, these metal-polymer sleeves exhibit large inner diameter tolerance fluctuation, making it challenging to achieve tight dimensional control. This difficulty is partly due to the inability to machine polymer sleeves post press-fitting into the bearing housing. Furthermore, recent research has highlighted the adverse environmental impacts associated with PTFE products.

Alternative solutions, such as bi-metal sleeves and Polyether Ether Ketone (PEEK) sleeves are actively evaluated. These offer the distinct advantage of allowing post-installation machining, enabling much tighter control over the inner diameter tolerances of the bearing. Achieving optimized clearance reduces the misalignment of gears [10];thereby mitigating stress on both the shaft and the sleeve, and also preventing creation of larger leakage paths between gear teeth tip and housing. Precise bearing technology can contribute to lowering the volumetric losses and thereby lowering the ZDS of the pump.

6.1.2. Radial gap compensation

Volumetric loss poses a significant challenge during low-speed pump operation, largely due to leakage across the radial gap between the housing and gear teeth tips. To mitigate this, novel designs actively reduce radial gap leakage. One promising approach involves incorporating a radial gap compensation element within the pump. This concept, state-of-the-art in internal gear pumps, dynamically adjusts the clearance between the gear teeth and the housing wall in response to operating pressure, thereby minimizing the leakage path [11]. **Figure 9** illustrates a proposed design featuring a radial gap compensation lid integrated into the pressure-side housing wall [12]. This lid is engineered to automatically adjust its position based on varying operating pressures. During high-pressure operation, the lid is pushed towards the gears, effectively reducing the clearance and thus dynamically controlling and minimizing volumetric loss through this pathway. Numerous iterations of this concept explore the optimal shape, position, and impact of the lid on internal leakage.

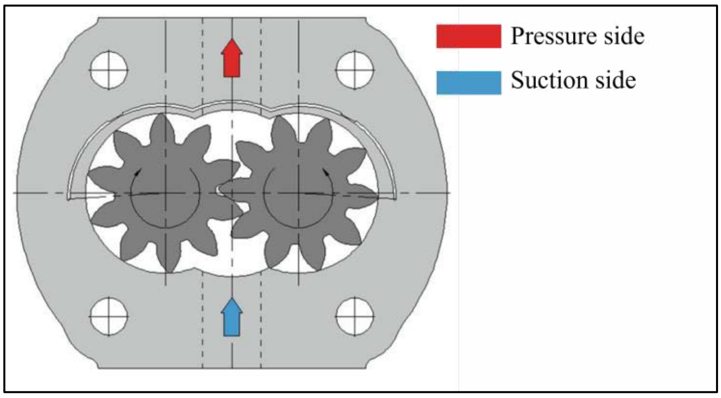

Figure 9: An example for radial gap compensation technology [12]

6.2. Enhancing the wear robustness and reduce friction between components

Enhanced wear robustness and reduced friction are crucial for improving both mechanical performance (e.g.: lower torque loss) and overall pump durability (e.g.: extended pump durability life). These improvements can be achieved through various methods, ranging from material property enhancements to advanced coating technologies. The subsequent section focuses on surface coatings that have demonstrated superior tribological properties – such as reduced wear, lower friction coefficients, and enhanced hardness – as documented in the literature.

6.2.1. Surface coatings for enhanced wear robustness of hydraulic components

Surface coatings are critical in tribology for reducing friction, mitigating wear, and enhancing the overall tribological performance of mechanical components [13]. For low-speed operation, wear on critical components like bearings and gears remains a significant challenge. Various coating materials, including Diamond-Like Carbon (DLC), Molybdenum Disulfide (MoS2), and Nickel-Molybdenum-Phosphide (Ni-Mo-P), are known to improve the tribological properties of coated parts [14] [15].

Specifically, applying DLC coatings to gears is documented to reduce friction at interfaces such as the gear-to-bearing contact and between the gear shaft and bearing sleeve. This friction reduction consequently minimizes torque loss and mitigates wear on these critical components. Moreover, reduced friction is expected to reduce the wear, enabling more prolonged and reliable operation under challenging low-speed conditions.

7. CONCLUSION

The electrification of mobile hydraulic applications, particularly in material handling, requires efficient electric-hydraulic systems capable of low-flow operation without traditional valving inefficiencies. This demands that EGPs operate effectively at low speeds, directly enhancing system efficiency and reducing costs. However, continuous operation (20000 operating hours) of these pumps at low speeds (< 500 rpm), high pressures (up to 280 bar), and elevated temperatures (80 °C) presents significant challenges, including volumetric losses and wear on bearings and gears.

This paper systematically addresses these requirements and challenges. The investigation utilized Bosch Rexroth's specific low-speed parameters: "zero delivery speed (ZDS)" and "hydrodynamic speed limit (HSL)". ZDS, a critical determinant of minimum pump operation, is significantly affected by temperature and pressure, increasing with temperature and following a non-linear (parabolic) curve with pressure. The HSL is crucial for minimizing torque loss and reducing component wear; operating below this limit drastically increases torque loss. Similar to ZDS, the HSL also rises with both temperature and pressure.

To overcome these low-speed challenges, the paper reviews and compiles practical, research-backed solutions. Specialized surface coatings are shown to directly mitigate wear, while advanced bearing technology and radial gap compensation offer promising approaches to minimize volumetric losses.

In conclusion, this work synthesizes the essential requirements and operational challenges of low-speed EGPs. It further highlights Bosch Rexroth's capabilities for their thorough investigation and identifies practical solutions for optimizing performance. Integrating these insights provides a clear path for EGPs to reliably and efficiently meet the stringent low-flow demands of electrified mobile hydraulic applications. This advancement will enable more sustainable and cost-effective electrified material handling systems.

8. REFERENCES

[1] A. Lajunen, P. Sainio, L. Laurila, J. Pippuri-Mäkeläinen and K. Tammi, "Overview of powertrain electrification and future scenarios for non-road mobile machinery," *Energies,* vol. 11, no. 5, p. 1184, 2018.

[2] M. d. F. Ramos, D. A. d. L. Brandao, D. P. V. Galo, B. d. J. Cardoso Filho, I. A. Pires and T. A. C. Maia, "A Study on the Performance of the Electrification of Hydraulic Implements in a Compact Non-Road Mobile Machine: A Case Applied to a Backhoe Loader," *World Electric Vehicle Journal,* vol. 15, no. 4, p. 127, 2024.

[3] L. J. Love, E. Lanke and P. Alles, "Estimating the impact (energy, emissions and economics) of the US fluid power industry," Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), 2012.

[4] N. D. S. A. Santos, V. R. Roso and M. T. C. Faria, "Review of engine journal bearing tribology in start-stop applications," *Engineering Failure Analysis,* vol. 108, p. 104344, 2020.

[5] M. Rundo, "Models for flow rate simulation in gear pumps: A review," *Energies,* vol. 10, pp. 1996-1073, 2017.

[6] F. Du, D. Li, X. Sa, C. Li, Y. Yu, C. Li, J. Wang and W. Wang, "Overview of Friction and Wear Performance of Sliding Bearings," *Coatings,* vol. 12, no. 9, p. 1303, 2022.

[7] B. Novaković, L. Radovanović, N. Zuber, D. Radosav, L. Djordjević and M. Kavalić, "Analysis of the influence of hydraulic fluid quality on external gear pump performance," *Eksploatacja i Niezawodnosc - Maintenance and Reliability,* vol. 24, no. 2, pp. 260-268, 15 03 2022.

[8] P. Michael, H. Khalid and T. Wanke, "An Investigation of External Gear Pump Efficiency and Stribeck Values," *SAE Technical Papers,* vol. 8, September 2012.

[9] M. Kalin, I. Velkavrh and J. Vižintin, "The Stribeck curve and lubrication design for non-fully wetted surfaces," *Wear,* vol. 267, no. 5-8, pp. 1232-1240, 2009.

[10] P. Szwemin and W. Fiebig, "The Influence of Radial and Axial Gaps on Volumetric Efficiency of External Gear Pumps," *Energies,* vol. 14, no. 15, p. 4468, 2021.

[11] P. Osiński and U. Warzyńska, "FEM Strength Analysis of Circumferential Compensation with Integrated Lips in Gear Pumps," *Energies,* vol. 15, no. 7, p. 2691, April 2022.

[12] P. Osiński, "Strength Calculation Methodology for Circumferential Backlash Compensation with Integrated Lips," in *Advances in Hydraulic and Pneumatic Drives and Control 2020*, Cham, 2021.

[13] I. P. Okokpujie, L. K. Tartibu, H. O. Musa-Basheer and A. O. M. Adeoye, "Effect of Coatings on Mechanical, Corrosion and Tribological Properties of Industrial Materials: A Comprehensive Review," *Journal of Bio- and Tribo-Corrosion,* vol. 10, no. 1, p. 2, 2023.

[14] A. K. Sharma, N. Kumar, A. K. Das and M. Kumar, "Ni-Mo-P coatings on thrust plate of a gear pump to enhance its mechanical, tribological, and corrosion resistance properties," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 238, no. 8, pp. 1196-1211, July 2023.

[15] D. K. Rajak, A. Kumar, A. Behera and P. L. Menezes, "Diamond-Like Carbon (DLC) Coatings: Classification, Properties, and Applications," *Applied Sciences,* vol. 11, no. 10, p. 4445, May 2021.

Biographies

Photograph

Nandakumar P S received the bachelor's degree in Mechanical engineering from Vellore Institute of Technology in 2020, and the master's degree in Energy engineering and management from National Institute of Technology-Calicut in 2024. He is currently working as an Engineer at the Advanced engineering department of Bosch Rexroth. His research areas include hydraulic systems with a focus on external gear pumps and thermo-fluid interaction.

Vishnudas Ramaswamy received the bachelor's degree in Mechanical engineering from Amrita School of Engineering in 2010, the master's degree in Fluids Engineering from the National Institute of Technology Allahabad in 2012 , and the philosophy of doctorate degree in Fluid Mechanics from the Indian Institute of Technology Madras in 201, respectively. He is currently working at the Advanced Engineering Department of Bosch Rexroth India Pvt. Ltd. His research areas include fluid power systems, fluid mechanics, computational fluid dynamics, and multiphase flow.

Stefan Kock received his Mechanical Engineering degree from the Technical University of Dresden, Germany, and his Ph.D. from RWTH Aachen University, where his research focused on wind turbine drive trains and torque measurements. He is currently Team Leader for Advanced Engineering for External Gear Units at Bosch Rexroth. His research areas include drive train technology, mechatronic systems, fatigue assessment, finite element method (FEM), and fluid power drives.

Martin Laube received his Diploma degree as Dipl.-Ing. (univ.) in mechanical engineering from the Technical University of Munich (TUM) in 1996. He specialized during his studies in the field of Design and Development with a focus on machine elements, vehicle technology and fluid technology. He started his industrial career in 1996 as a development engineer for railway systems at Mannesmann Rexroth, Lohr a. Main. After holding various positions in sales and engineering for industrial applications at Mannesmann Rexroth and Bosch Rexroth (since 2001), he assumed the position of Engineering Director for Hydraulic Power Units, Manifolds and Systems at Bosch Rexroth AG in 2013. Since July 2024, he has been Vice President and Head of Product Area External Gear Units in the Business Unit Mobile Components at Bosch Rexroth AG.