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INVESTIGATING EXTERNAL GEAR PUMP EFFICIENCY AT VERY LOW SPEEDS WITH GRAPHENE NANOFLUIDS

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ABSTRACT

Experimental investigations are performed to assess the operational efficiency of external gear pumps under high-pressure conditions, with a specific focus on varying shaft rotation speeds. These analyses encompass a broad range of rotational velocities, spanning from conventional to remarkably low speeds, reaching a minimum threshold of 150 RPM. At such reduced speeds, both volumetric and torque losses rise significantly, posing notable challenges to pump performance. Additionally, the lubrication conditions at such modest velocities are often compromised, further constraining the operational range of gear pumps, and limiting the efficacy of pump-controlled systems reliant on speed modulation.

The primary objective of the current investigations is to assess the potential efficacy of nanofluids in enhancing pump performance, particularly under the demanding operational conditions delineated above. This entails scenarios where pump loads are very high, and operational speeds are diminished to the extent of miss proper lubrication. Consequently, the study presents a comparative analysis of external gear pumps operating with conventional fluids versus those integrated with graphene nanoparticle-infused fluids. Performance metrics, in terms of volumetric and mechanical-hydraulic efficiency, are evaluated to gauge the impact of nanofluids on overall pump energy performance.

The findings of this study give quantitative insights into the influence of nanofluids on gear pump efficacy, thereby offering data for subsequent modeling activities. Such analyses hold relevance when control of gear pumps through variable speed logic is needed, as they provide understanding of the potential benefits and limitations associated with the adoption of nanofluid-enhanced pump systems.

Keywords: Low speed external gear pump, graphene nanofluid, volumetric efficiency, torque efficiency

1. INTRODUCTION

Valve-controlled systems typically rely on fixed displacement pumps with flow control achieved through throttling valves, leading to energy losses and decreased efficiency [1]. Hydraulic pump-controlled systems offer superior efficiency compared to valve-controlled systems [2]. These systems adjust their output flow rate according to the required load, resulting in reduced energy consumption during part-load operation, playing a crucial role in the field of fluid power [3]. They rely on different types of hydraulic pumps, including gear pumps, vane pumps, piston pumps, and axial piston pumps. Each type of pump has its own advantages and limitations, depending on factors such as flow rate, pressure requirements, and efficiency [4].

Pump-controlled systems can be divided into two categories depending on the adopted logic for flow control. The first category includes systems based on variable displacement pumps [5]. In this case, flow control is entrusted to the pump, which operates at a fixed speed. This setup offers the flexibility to manage flow from zero to the maximum allowed by the pump, reflecting the unique characteristics of variable displacement machines, typically axial piston pumps, albeit with a relatively high cost. The second category comprises systems that control the flow delivery based on the speed variability of a fixed displacement pump [6]. Notably, this logic choice can forgo piston pumps in favor of more cost-effective external gear machines. However, fixed displacement inherently limits system flexibility, as the pump speed cannot be reduced below a certain value. Therefore, the primary limitation of pump-controlled systems with fixed displacement pumps lies in the practical impossibility of completely stopping flow, owing not to actuation (typically a motor or servo motor controlled for speed), but to intrinsic pump limitations.

Focusing on external gear pumps, due to their widespread use across various applications, low rotational speeds pose challenges for both lubrication and fluid transfer capacity [7]. Lubrication requires achieving suitable hydrostatic regime for proper pump operation, while the acceptable conditions for fluid transfer occur only beyond the minimum speed threshold. Key parameters for comprehensively describing pump behavior are hydraulic mechanical efficiency and volumetric efficiency, both of which are functions of pressure and machine operating speed. They typically exhibit low and less tolerable values when pressure is high, and speed is low. Consequently, it's unsurprising that pump-controlled systems with fixed displacement pumps, typically gears, cannot be adopted when very low or no flow logic control is required. Thus, extending the operating range (in terms of rotational speed) of gear pumps downward would be highly beneficial.

It's worth noting that there is a wealth of scientific literature on external gear pumps, organized into various research paths. Research activities in the field of external gear pumps in fluid power encompasses a wide range of topics, reflecting the ongoing advancements and challenges in this area.

Enhancing the efficiency of external gear pumps is a crucial area of research. This includes studying the design parameters, materials, and manufacturing processes to minimize energy losses and improve overall efficiency. External gear pumps can produce noise and vibrations during operation, which can be undesirable in various applications. Research focuses on developing techniques to reduce noise and vibration levels through innovative designs, materials, and damping methods [8,9]. Understanding the wear mechanisms in external gear pumps and developing effective lubrication strategies are essential for improving pump reliability and longevity. Research in this area explores wear-resistant materials, lubricant formulations, and lubrication systems to minimize wear and prolong component life [10,11]. Cavitation, which occurs when the pressure drops below the vapor pressure of the fluid, can lead to performance degradation and damage to pump components. Research aims to understand the factors contributing to cavitation in external gear pumps and develop mitigation techniques to prevent its occurrence [12,13]. Temperature fluctuations can affect the performance and reliability of external gear pumps. Research focuses on thermal management strategies, such as cooling systems and heat dissipation techniques, to maintain optimal operating temperatures and prevent overheating [14]. Seals play a critical role in maintaining fluid integrity and preventing leakage in external gear pumps. Research explores advancements in seal materials, designs, and sealing technologies to enhance reliability and reduce maintenance requirements [12,15,16]. External gear pumps may experience transient conditions during startup, shutdown, or sudden changes in operating conditions. Research investigates the transient behavior of pumps and develops control strategies to optimize performance, reduce energy consumption, and minimize system instability [17]. Research focuses on the integration of pumps with hydraulic systems, including control algorithms, system optimization, and compatibility with other components such as valves and actuators. Implementing condition monitoring techniques can help detect potential issues in external gear pumps early, allowing for proactive maintenance and minimizing downtime. Research explores sensor technologies [18], data analytics, and predictive maintenance strategies for monitoring hydraulic fluid and pump health or performance.

Despite the richness and quality of the activities undertaken so far, there is undoubtedly a gap in exploring the behavior of pumps at low and very low rotational speeds. This should not come as a surprise considering that until recently, variable-speed electric drives were not available, and the need and awareness of increasing the energy efficiency of hydraulic systems were not fully matured. On the other hand, it is likewise evident that, all other factors being equal, pump efficiencies depend on the characteristics of the hydraulic fluid. Now, alongside traditional hydraulic fluids, eco-friendly fluids are becoming increasingly prominent [19]. These fluids not only mitigate the environmental impact of hydraulic systems but also contribute to performance improvements [20]. In this context, which certainly tends to introduce several novelties associated with unconventional fluids, nanofluids also emerge. Nanofluids are dispersions of solid nanoparticles in a liquid, typically represented by traditional hydraulic fluid. Solid nanoparticles are dispersed in the fluid to support lubrication, improving the interaction between elements in relative motion. The literature contains a relatively rich body of contributions documenting the effects of nanofluids, or nanolubricants, on friction. Depending on the type of nanoparticle used, a generalized reduction in friction coefficients is observed due to the presence of solid particles. Among the most interesting particles, there is graphene or exfoliated graphite. Graphene particles are "almost" two-dimensional carbon (graphite) particles organized in sheets, with the capability to intervene in the friction mechanism between surfaces in relative motion. In a previous study, the authors reported the results of initial investigations into the impact of graphene nanofluids on volumetric and mechanical-hydraulic efficiency [21]. The experiments revealed that the nanofluid affects mechanical-hydraulic and volumetric losses. Under the operating conditions considered, moderate but significant effects on torque efficiency and evident benefits on volumetric efficiency were observed. The aim of the current work is to experimentally investigate the influence of graphene nanofluid on the efficiency of external gear pumps operating at very low speeds, down to 150 rpm. The results of previous experiments [21] suggest that any benefits of graphene nanofluids on torque efficiency may manifest under conditions when loading tends to compromise hydrostatic lubrication within the pump (low rotational speed and high pressure).

2. MATERIALS AND METHODS

2.1 Pump efficiency

According to Eq. (1), the pump overall efficiency, η_{pump}, is expressed as the ratio between the hydraulic power P_{hyd} and the mechanical power at pump shaft P_{mech}

$$\eta_{pump} = \frac{P_{hyd}}{P_{mech}} \tag{1}$$

Eq. (1) is rewritten in terms of torque at pump shaft C, pump speed n is the pump flow rate Q and load pressure Δp, Eq. (2).

$$\eta_{pump} = \frac{Q \Delta p}{nC} \tag{2}$$

Eq. (3) reports the overall efficiency as the product of volumetric efficiency η_v and torque efficiency η_t, where V_{disp} is the pump displacement.

$$\eta_{pump} = \frac{Q}{V_{disp} n} \frac{V_{disp} \Delta p}{C} = \eta_v \, \eta_t \tag{3}$$

Eq. (4) defines the torque efficiency as

$$\eta_t = \frac{C_{th}}{C} = \frac{V_{disp} \Delta p}{C} \tag{4}$$

where C_{th} is the theoretical torque at pump shaft. The actual displacement of the pump is experimentally evaluated through Eq. (5), where Q_0 is the pump flow rate and n_0 is the shaft speed, both measured at zero load condition, to practically eliminate the volumetric losses due to compressibility and leakage.

$$V_{disp} = \frac{Q_0}{n_0} \tag{5}$$

Eq. (6) reports the volumetric efficiency, where Q is the experimentally measured flow rate and Q_{th} is the theoretical flow rate, namely the product of the pump displacement calculated with Eq. (5) and the pump speed.

$$\eta_v = \frac{Q}{Q_{th}} \tag{6}$$

2.2 Experimental set-up

The details of the experimental set-up are reported in [21]. nevertheless, the main features of the system are resumed in the following. Figure 1 reports a view of the pump testbed available at Fluid Power Laboratory of DIIEM – Roma TRE. The mechanic-hydraulic sketch of the pump test bed is reported in Figure 2.

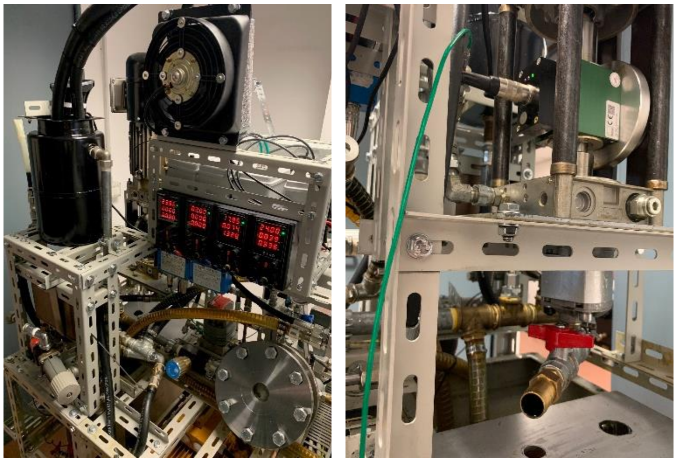

FIGURE 1: FRONT VIEW OF PUMP TEST BED AT FLUID POWER LABORATORY OF DIIEM – ROMA TRE, LEFT; REAR VIEW of TORQUE-METER AND EXTERNAL GEAR PUMP ASSEMBLY, RIGHT.

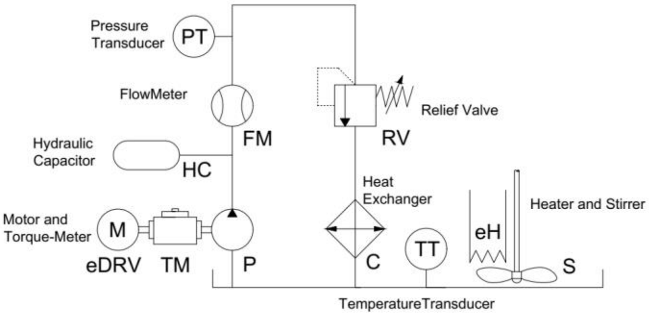

FIGURE 2: SKETCH OF THE HYDRAULIC SET-UP

The features of instrumentation and data acquisition systems are collected in Table 1.

TABLE 1: INSTRUMENTATION AND DAQ SYSTEM

	Component	Specification
eDRV	Electric drive	4-pole asynchronous motor and frequency converter
TM	Torque meter and optical encoder	Burster 8661
PT	Pressure transducer	Kistler 4005 piezo-resistive transducer
FM	Flow meter	VS 0.1 - VSE Volumentechnik GmbH
TT	Temperature transducer	Class 1/10 DIN RTD
DAQ System	IO module	National Instruments PXIe 6143

2.3 Pumps under test

The investigation is carried out on two external gear pumps, (Pump 1 and Pump 2) belonging to the same dimensional class (01-Group). The pumps have different nominal displacement, 0.8 cc/rev and 2.7 cc/rev, respectively.

Pump 1 Pump 2

FIGURE 2: VIEW OF THE PUMPS UNDER INVESTIGATION

2.4 Tested fluids

The experiments are formerly carried out using the reference fluid, here called RF. The same fluid has been used to prepare the "nanofluid", by adding graphene nanoparticles. The carbon nanoparticles are obtained by liquid-phase-exfoliation of graphite. Each particle is a "Quasi-2-Dimensional" element, with 10 nm thickness along Z axis and 100-200 nm length along the other axes (X, Y), as reported in Figure 3. Table 2 reports the features of the fluids. For each fluid, the test points sweep the very low-speed operating range of the pump. Pump speed ranges from 150 RPM to 350 RPM, whereas delivery pressure level ranges from 60 to 180 bar.

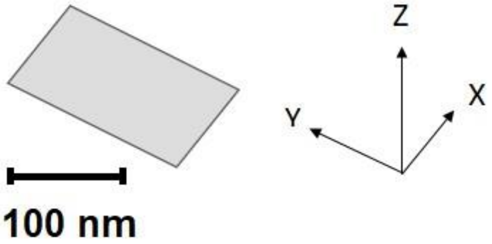

FIGURE 3: GRAPHENE NANOPARTICLE SKETCH

TABLE 2: TESTED FLUIDS

Reference Fluid (RF)	**Viscosity** μ [Pa s]	**Density** ρ [kg/m^3]
ISO VG 46	0.0391	880
	Graphene mass concentration	**Base fluid**
Nanofluid (GX)	0.5%	Reference Fluid (RF)

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3. RESULTS AND DISCUSSION

Table 3 reports the measured displacement of the two pumps under investigation, according to Eq. (5), in comparison to the nominal values.

TABLE 3: NOMINAL AND MEASURED PUMP DISPLACEMENT

	Displacement V_{disp}	
	Nominal	**Measured**
Pump 1	0.8 cc/rev	0.835 cc/rev
Pump 2	2.7 cc/rev	2.620 cc/rev

Figures 4 and 5 display the performance graphs obtained from the experimental activities for Pump 1 and Pump 2, respectively. The graphs in the first column report volumetric efficiency, the second column shows the torque-efficiency, and the third column presents the overall efficiency. Rows, on the other hand, correspond to rotational speed. The top row refers to 350 rpm, while the last row shows the results for the minimum speed (150 rpm). Before delving into the results, it's worth remembering the findings from [21], which allowed studying the impact of graphene fluids on a pump similar to Pump 1, albeit in the realm of typical speeds for industrial gear pumps (ranging from 750 rpm up to 3000 rpm). The experimental campaigns concluded that adopting graphene nanofluid led to improved volumetric efficiency, albeit with a limited decline in torque efficiency. Therefore, this study highlighted the significant influence of nanofluid on pump performance, particularly in terms of fluid displacement capability (and thus, the pump's ability to resist leakage), and to a lesser extent, its adverse effects on mechanical-hydraulic or torque losses. This could be acceptable, given that when the pump operates within typical speed ranges, hydrostatic lubrication conditions should ideally be achieved. Thus, nanoparticles could behave like contaminants that disrupt a system operating around an optimum point, thereby degrading its performance. Lower operating speeds compromises the hydrostatic lubrication setup, exposing pump components to potential benefits arising from contact between moving parts mediated by nanoparticles. Figure 4 illustrates the effect of nanofluid on Pump 1 behavior. At constant pressure, pump performance declines as speed decreases. The performance drop associated with decreasing pump speed becomes more severe with higher pressures. Compared to trends observed with the reference fluid, significantly better performance is observed when using nanofluid. Regarding volumetric efficiency, nanofluid has a significant impact at all tested speeds, with increasingly effective improvement as speed decreases. As for torque efficiency, the 350-rpm speed represents the threshold beyond which further reductions in speed lead to positive effects on torque-loss reduction, particularly at high pressures. Table 4 highlights the percentage differences observed in volumetric efficiency when using nanofluid, while Table 5 refers to mechanical-hydraulic efficiency.

TABLE 4: % DIFFERENCES ON VOLUMETRIC EFFICIENCY-Pump 1

Pump 1				
Shaft speed (rpm)	Pressure (bar)	Volumetric efficiency		% difference
		RF	GX	
350 rpm	170	0.78	0.83	+6.4
	130	0.83	0.86	+3.6
	60	0.91	0.92	+1.1
250 rpm	170	0.71	0.77	+8.5
	130	0.77	0.81	+5.2
	60	0.87	0.90	+3.4
150 rpm	170	0.52	0.62	+19.2
	130	0.62	0.69	+11.3
	60	0.80	0.84	+5.0

TABLE 5: % DIFFERENCES ON TORQUE EFFICIENCY-Pump 1

Pump 1				
Shaft speed (rpm)	Pressure (bar)	Torque efficiency		% difference
		RF	GX	
350 rpm	170	0.88	0.88	0.0
	130	0.88	0.87	-1.1
	60	0.84	0.83	-1.2
250 rpm	170	0.85	0.88	+3.4
	130	0.87	0.88	+1.1
	60	0.86	0.84	-2.4
150 rpm	170	0.77	0.85	+9.4
	130	0.85	0.87	+2.3
	60	0.81	0.84	+3.6

Figure 5 reports the graphical trends of the efficiencies obtained in the case of Pump 2. With regard to results related to the reference fluid, efficiency trends are poorer compared to those observed with the other pump, particularly under the most severe loading conditions.

TABLE 6: % DIFFERENCES ON VOLUMETRIC EFFICIENCY-Pump 2

Pump 2				
Shaft speed (rpm)	Pressure (bar)	Volumetric efficiency		% difference
		RF	GX	
350 rpm	180	0.68	0.76	+11.8
	150	0.73	0.79	+8.2
	60	0.87	0.9	+3.4
250 rpm	180	0.51	0.69	+35.3
	150	0.6	0.72	+20.0
	60	0.81	0.85	+4.9
150 rpm	180	0.17	0.31	+82.4
	150	0.51	0.63	+23.5
	60	0.65	0.75	+15.4

TABLE 7: % DIFFERENCES ON TORQUE EFFICIENCY-Pump 1

Pump 2				
Shaft speed (rpm)	Pressure (bar)	Torque efficiency		% difference
		RF	GX	
350 rpm	170	0.81	0.86	+6.2
	130	0.85	0.88	+3.5
	60	0.83	0.84	+1.2
250 rpm	170	0.72	0.83	+15.3
	130	0.82	0.87	+6.1
	60	0.82	0.83	+1.2
150 rpm	170	0.64	0.72	+12.5
	130	0.72	0.83	+15.3
	60	0.78	0.81	+3.8

The use of nanofluid leads to significant increases in volumetric and torque efficiency values. It's also noteworthy that in this case, the effect on mechanical-hydraulic efficiency is more pronounced, becoming evident starting from 350 rpm. Tables 6 and 7 present the percentage differences observed in efficiencies when using nanofluid.

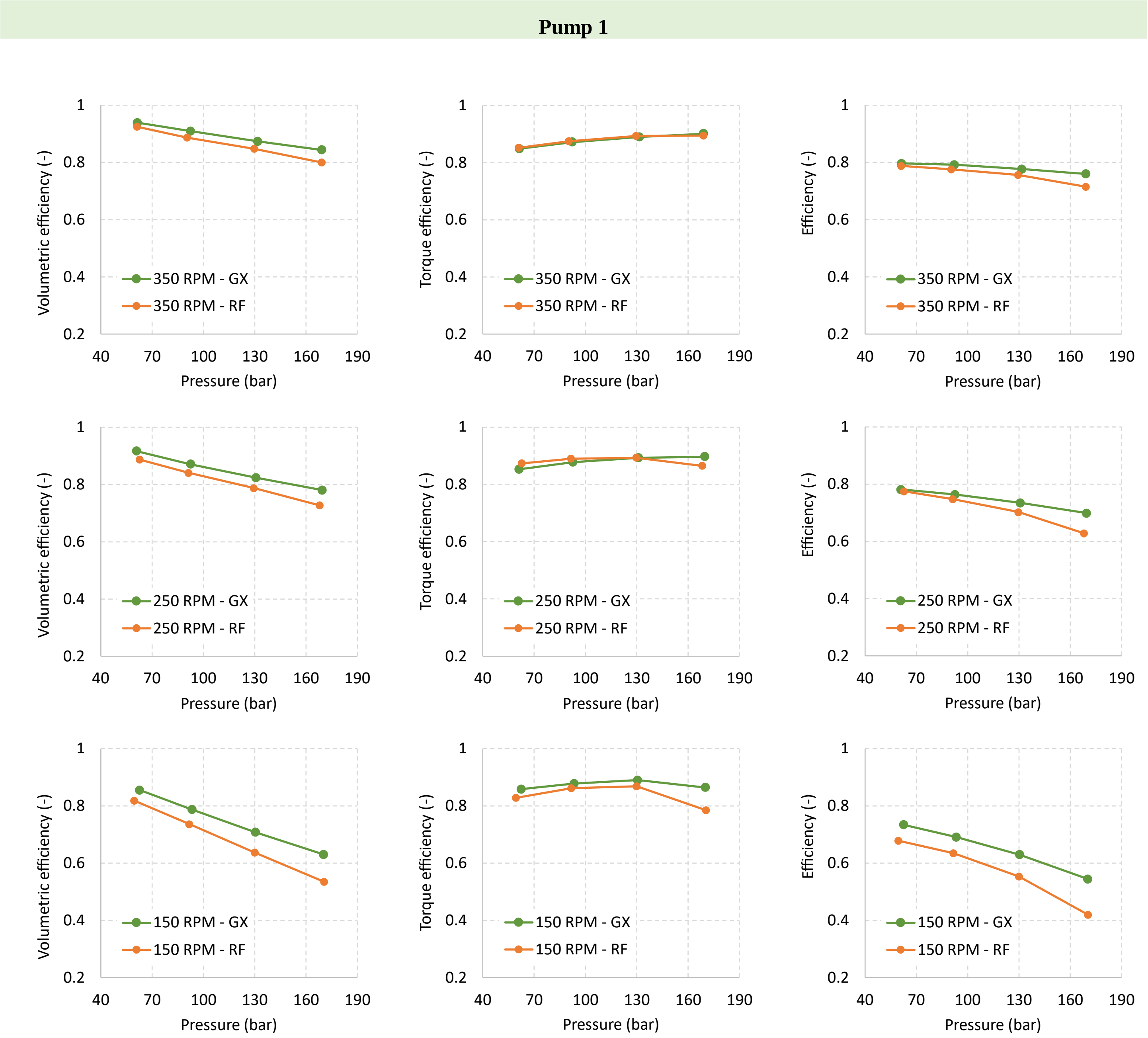

FIGURE 4: PERFORMANCE CHARTS OF PUMP 1 AT VERY LOW SPEED

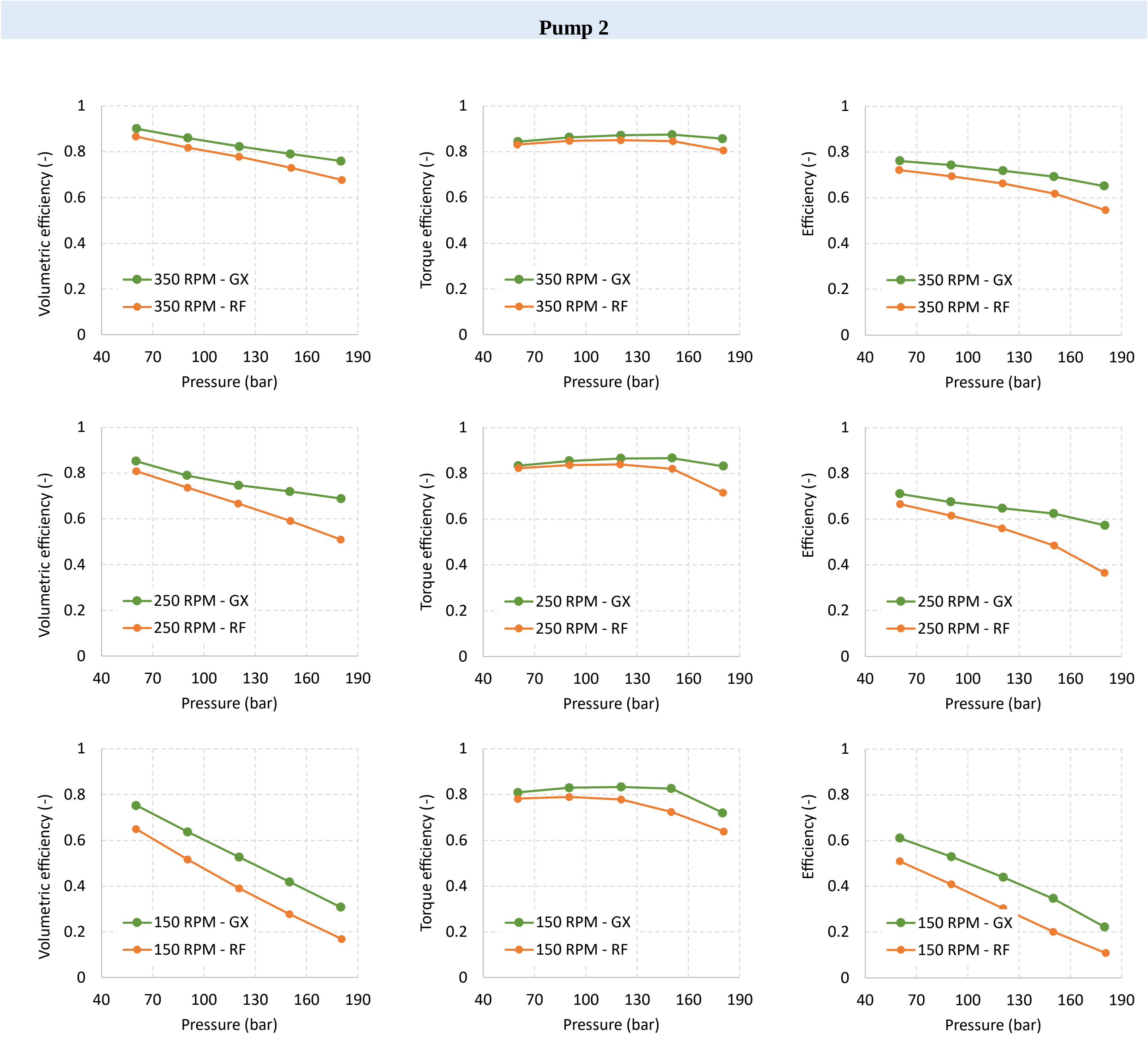
Pump 2

FIGURE 5: PERFORMANCE CHARTS OF PUMP 2 AT VERY LOW SPEED

4. CONCLUSION

Experimental investigations have allowed for the characterization of pump performances at very low rotational speeds and have highlighted the influence of graphene nanofluid on pump efficiency. The use of nanofluid is associated with a significant increase in volumetric efficiencies and mechanical-hydraulic efficiencies, the magnitude of which is particularly significant under more severe operating conditions.

Regarding volumetric efficiency, nanofluid leads to a reduction in leakage losses, taking into consideration that the presence of solid particles does not alter the fluid's compressibility modulus. Although literature studies aimed at understanding how nanofluid affects the leakage mechanism are not yet available, it may be inferred that the presence of nanoparticles within the sealing clearances limits the leakage flow.

As for the effect on mechanical-hydraulic efficiency, it is important to highlight that the benefits are most apparent under severe load. In such conditions, nanofluid, or nanoparticles, significantly reduce the torque losses. Considering the benefits also brought about on volumetric efficiency, substantial improvements in overall efficiency are achieved, reaching up to 100% under the most severe loading conditions.

The pumps belong to the same size class but differ in displacement. Pump 2, with a larger displacement, is inherently more stressed, under the same pressure and speed, compared to Pump 1, whose modest displacement places it at the lower end of its size class. From this perspective, it seems reasonable that Pump 2 derived greater benefits in torque efficiency from nanoparticles, assuming they can intervene under high-stress friction phenomena, in agreement with the literature on graphene nanofluid tribology.

The obtained results enrich the literature with valuable information describing pump behavior at low and very low speeds and provide useful data to build and validate models for the analysis of pump-controlled systems over extensive speed ranges.

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