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EXTERNAL GEAR PUMP PERFORMANCE WITH GRAPHENE HYDRAULIC FLUID

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ABSTRACT

The literature reports that the addition of nanoparticles to hydraulic fluids significantly improves their fundamental properties such as viscosity index, lubricity, and anti-wear performance. Among the others, graphene-based nanomaterials are a potential candidate for hydraulic nanofluids due to their atomic thickness, high thermal conductivity, high thermal stability, and ecological nature.

Based on the research reported so far at tribological level, it is interesting to assess whether, and to what extent, the properties of nanofluids have an impact on hydraulic components performance. Accordingly, the article is devoted to highlight the effects of graphene based nanofluid on pump performance. Two formulations of graphene hydraulic fluid are prepared with the same standard mineral oil and graphene particles.

Pump performance is expressed in terms of volumetric efficiency and torque efficiency, measured in a wide range of pump speed and load pressure. The pump efficiency has been previously benchmarked with the standard hydraulic fluid. Then, for each formulation, experimental tests have been compared to the reference case, allowing quantitative performance comparison. The results have been lumped through loss coefficients, providing new data for modeling activities and for research and development in the field of hydraulic nanofluids.

Keywords: External gear pump, graphene, volumetric efficiency, torque-efficiency, nanofluids

1. INTRODUCTION

Beside the power transfer, the hydraulic fluid must guarantee reduced friction and wear through lubrication, protection from corrosion and many other fundamental features such as good response to thermal stresses, to contamination, to oxidation.

It is well known that additives are used to meet the required features of the fluids [1]. Various compounds are currently available to ensure the correct operation of hydraulic components and systems [2]. Since the 1990s, the possibility of using solid-type additives in the form of nanoparticles has been explored, such as molybdenum disulphide, widely used in many fields [3]. More recently, other nanoparticles have been identified to obtain significant improvements in friction and wear reduction, increase in heat exchange, and protection from corrosion [4]. Among the various nanoparticles available or potentially useful, a fundamental role is played by graphene [5,6]. Introduced in 2004, graphene has shown an important aptitude to be used in many fields such as the technology of osmotic membranes [7], super capacitors [8], molecular electronics [9] just to name a few. Graphene sheets have shown their potential to serve as an additive for lubricants, thermal vectors, and hydraulic fluids [10]. In the light of the most recent research, this nanomaterial retains unique chemical-physical properties that ensure very high thermal, tribological and rheological properties [11].

Dedicated insights have started unveiling how the graphene nanoparticles improve the lubricating properties of fluids [12]. Although further research is needed to address many open questions, it has been highlighted that the two-dimensional structure of graphene is the key feature influencing friction between surfaces, while increasing the rate of heat transfer [13].

The literature reports several contributions aimed at deepening the tribology of lubrication with graphene nano-fluids [14,15]. Some contributions have taken hydraulic fluids into consideration, highlighting how the nanoparticles additives bring interesting benefits with relatively low concentrations of graphene, typically in the range 0.05% - 0.5% by mass. An investigation on tribological properties of graphene and MoS_2 nanoparticles as additives in aviation hydraulic oil is reported in [16]. In [17] the thermo-physical and tribological properties of an hydraulic nanofluid is investigated, highlighting the potential of reducing friction in a mechanical system. In [18] the authors have pointed out that the excellent lubrication function of T-GO hybrid hydraulic oil depends on nanoparticles dispersion stability and on the formation of graphene-like tribo-film, reducing friction and protecting the tribo-interfaces against wear. In [19] the effect of modified graphenes on the friction and wear performance and anti-oxidation performance of hydraulic oil was investigated by four-ball machine friction test and oxidation stability test. Three kinds of modification methods were used to modify the active functional groups of five graphenes with different thicknesses and different oxidation degrees to improve their dispersion stability in hydraulic oil. [20] evaluates the feasibility of improving the efficiency of hydraulic systems by modifying the thermophysical properties and rheological behavior of base hydraulic oil through nanoparticles.

All the studies reported so far are based on tribological experimental activities that allow the determination of friction coefficients and wear levels. It can be concluded that graphene based nanofluids ensure high performance from a tribological point of view, which is also linked to the greater heat exchange capacity.

Although the improvement of specific fluid properties (friction and heat transfer coefficients) undoubtedly represents a fundamental research step, it is necessary to explore to what extent the tribological properties of the nanofluids are reflected in the performance of components and systems in field or industrial applications. Thus, it is essential to investigate their influence when operating with real-scale components. In fact, the energy performances of the components, such as hydraulic pumps, are undoubtedly linked to the torque losses, that depend on tribology and, indirectly, on heat exchange. In the fluid power field, a strong interest is linked to the chance to improve the energy performance of components and systems.

The objective of this work is to investigate how the hydraulic pumps are influenced by graphene nanofluids, in terms of energy performance. As a first step in this direction, it was decided to pay attention to external gear pumps, as they are widely used in many areas of hydraulics.

The investigations are devoted to compare the energy performance of the pump operating with different types of fluid. A reference standard fluid, and two nanofluids that are obtained by adding 0.1% and 0.5% mass of graphene nanoparticles to the reference fluid.

The following section provides the complete description of the investigation approach, the experimental set-up, the fluids used and the test conditions.

2. MATERIALS AND METHODS

2.1 Pump efficiency

The pump overall efficiency, η_{pump}, is expressed as (1),

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

where P_{hyd} is the hydraulic power and P_{mech} is the mechanical power at pump shaft. Eq. (1) is rewritten as (2), where C is the torque at pump shaft, n is the pump speed, Q is the pump flow and Δp is the pressure load across delivery and inlet ports.

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

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

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

The torque efficiency is defined as (Eq. 4)

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

where C_{th} is the theoretical torque at pump shaft. The actual displacement of the pump is obtained by measuring pump speed and pump flow rate unloading the delivery volume, to practically eliminate the volumetric losses due to compressibility and leakage. Thus, the pump displacement is computed according to Eq. (5), where Q_0 is the measured flow rate and n_0 is the shaft speed.

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

The volumetric efficiency is expressed as (Eq. 6), where Q is the experimentally measured flow rate and Q_{th} is the theoretical flow rate.

$$\eta_v = \frac{Q}{Q_{th}} \qquad (6)$$

The theoretical flow rate is the product of the pump displacement calculated with Eq. (5) and the pump speed. The actual flow rate Q differs from the theoretical one Q_{th} due to volumetric losses.

2.2 Experimental set-up

The sketch of the experimental set-up is shown in Figure 1; an electric drive (eDRV) is coupled to the pump under test (P). The torquemeter (TM) is installed between pump and motor. The pump load is monitored via the pressure transducer (PT). Pressure pulsations induced by the pump are kept at a negligible level by the hydraulic capacitor (HC). The volumetric flow rate is measured through (FM), on the high-pressure side. The test pressure level is set through the relief valve (RV).

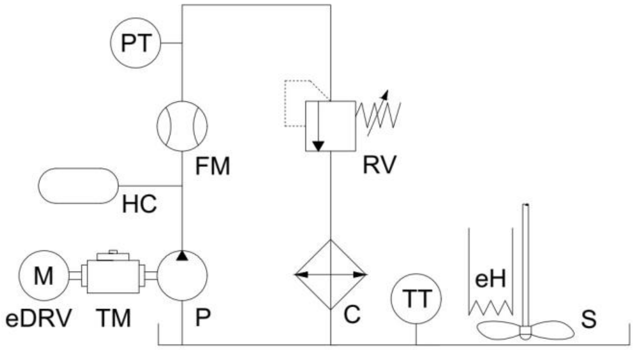


FIGURE 1: SKETCH OF THE HYDRAULIC SET-UP

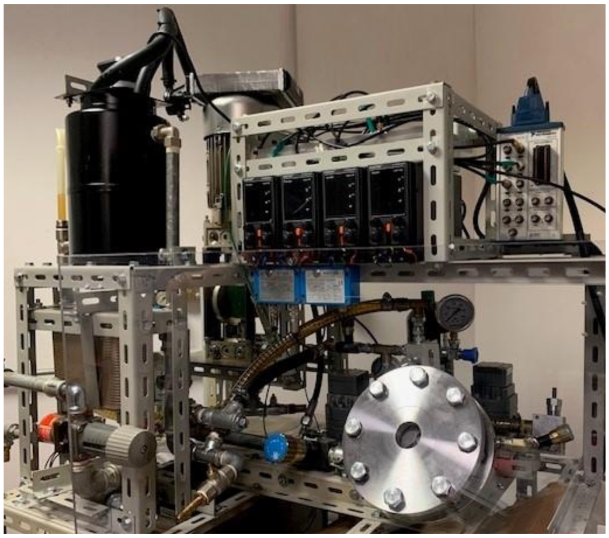


FIGURE 2: View of the hydraulic test rig at DIIEM – Roma TRE Fluid Power Laboratory

The tank temperature is measured by a temperature transmitter (TT) and it is continuously monitored during the tests. Fluid is thermally conditioned at the target temperature by the operation of the air-cooler downstream the pump (C), coordinated to the electric heater (eH). The mechanical stirrer (S) ensures the homogeneity of the fluid during the tests. TABLE 1 reports the main features of the adopted instrumentation. Figure 2 reports a view of the complete hydraulic test rig in laboratory. Figure 3 shows the torquemeter, the external gear pump and its main specifications.

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

a) **b)**

Dimensional class	Group 1
Peak load pressure	210 bar
Continuous load pressure	190 bar

FIGURE 3: a) Pump-torquemeter assembly; b) Detail of pump and feeding line.

TABLE 2: TESTED FLUIDS

	μ [Pa s]	ρ [kg/m^3]
Reference Fluid (RF) Eni OSO VG46	0.0391	880
	Graphene mass concentration	Base fluid
Nanofluid 1 – NF1	0.1%	ENI OSO VG46
Nanofluid 2 – NF2	0.5%	ENI OSO VG46

The experiments are formerly carried out using the reference fluid. The same fluid has been used to prepare the “nanofluids”, by adding graphene nanoparticles, obtained by liquid phase exfoliation, at different concentrations. Table 2 reports the features of the used fluids. For each fluid, the test points ($T_{i,j}$) sweep the proper operating range of the pump. Pump speed ranges from 750 RPM to 3000 RPM, whereas delivery pressure level ranges from 60 to 180 bar, as reported in Table 3.

TABLE 3: TEST CASES

Test cases		Delivery pressure (bar)				
		60	**90**	**120**	**150**	**180**
Pump shaft speed (RPM)	**750**	$T_{1,1}$	$T_{1,2}$	$T_{1,3}$	$T_{1,4}$	$T_{1,5}$
	1000	$T_{2,1}$	$T_{2,2}$	$T_{2,3}$	$T_{2,4}$	$T_{2,5}$
	1500	$T_{3,1}$	$T_{3,2}$	$T_{3,3}$	$T_{3,4}$	$T_{3,5}$
	2250	$T_{4,1}$	$T_{4,2}$	$T_{4,3}$	$T_{4,4}$	$T_{4,5}$
	3000	$T_{5,1}$	$T_{5,2}$	$T_{5,3}$	$T_{5,4}$	$T_{5,5}$

3. RESULTS AND DISCUSSION

Table 4 reports the measured pump displacement, according to Eq. (5), in comparison to the nominal value.

TABLE 4: NOMINAL AND MEASURED PUMP DISPLACEMENT

	Nominal	Measured
Displacement V_{disp}	0.8 cc/rev	0.855 cc/rev

With reference fluid (Figure 4), the best overall efficiency is obtained at 1500 RPM, regardless the load pressure. At higher speed, the efficiency sensitivity on pressure is unvaried. Despite lower values are observed, the trends have similar downward concavity and monotonous character, as in the case at 1500 RPM. At minimum speed (750 RPM) pump behavior is different. The efficiency loses the dependence on pressure. In the 60-110 bar range, the efficiency is relatively high, while in the 110-190 bar range, the pump performance differs considerably from those obtained in the other conditions, settling around the value of 0.8. At maximum pressure, low speed reduces performance (about 5 percentage points).

The trends of the volumetric and torque efficiencies give the chance to further discuss the overall performance of the pump. The volumetric efficiency, always dependent on pressure, is strongly influenced by pump speed. At 750 RPM the lowest values are obtained, which lead to differences in the order of 5-10%, depending on the case. The torque efficiency is affected by both load and speed; at low pressure, the pump shows better efficiency for low speed. At high pressure the differences are smaller, with higher performance. In the light of that, the "flat" overall efficiency trend at 750 RPM is mainly due to the behavior (shape) of volumetric efficiency trend, characterized by high pressure sensitivity in all test conditions and by a more marked sensitivity to pump speed.

The nanofluid NF1 (Figure 5) has appreciable effects on pump efficiency trends. The trends as a function of speed highlight the clear shift of the position of the maximum point, which moves to higher speed (1500 RPM). This effect comes with some decay in the performance of the machine in the range 750 -1500RPM. Looking at the volumetric and torque efficiency trends, it is possible to observe that the influence of the NF1 on the overall pump performance is mainly due to the alteration on torque efficiency. In fact, the volumetric efficiency trends, while showing slight deviations in the order of a percentage point, do not change "shape" or "character" in a significant way. On the other hand, the torque efficiency trends are affected by NF1 around 1000 RPM, thus altering the overall performance moving from RF to NF1.

By increasing the concentration of nanoparticles (NF2 – Figure 6), the overall performance of the pump becomes less dependent on the speed. This effect is well appreciable through the curves of overall efficiency as a function of pressure, that are close to each other. Overall efficiency alterations are appreciable, with a slight improvement at low speed in comparison to NF1. The volumetric efficiency show an improvement throughout the working range. It is especially well evident in the most critical conditions (at low speed), in the order of two percentage points. The torque efficiency undergoes variations which tend to compensate the improvement of volumetric efficiency. The trends as a function of speed show, also in this case, the shifted maximum at 1500 RPM, accompanied by a general but moderate decay in comparison to the reference fluid.

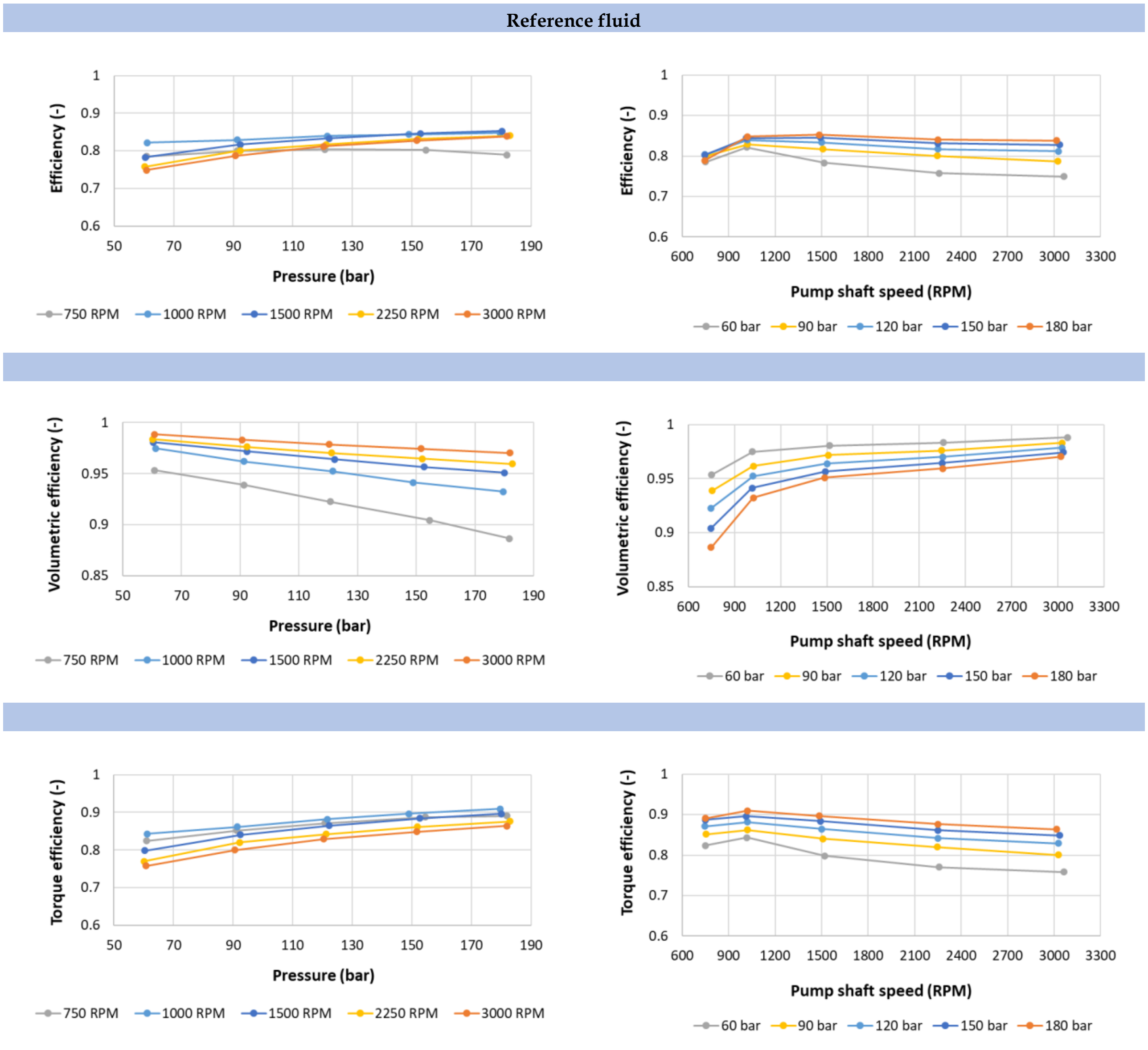
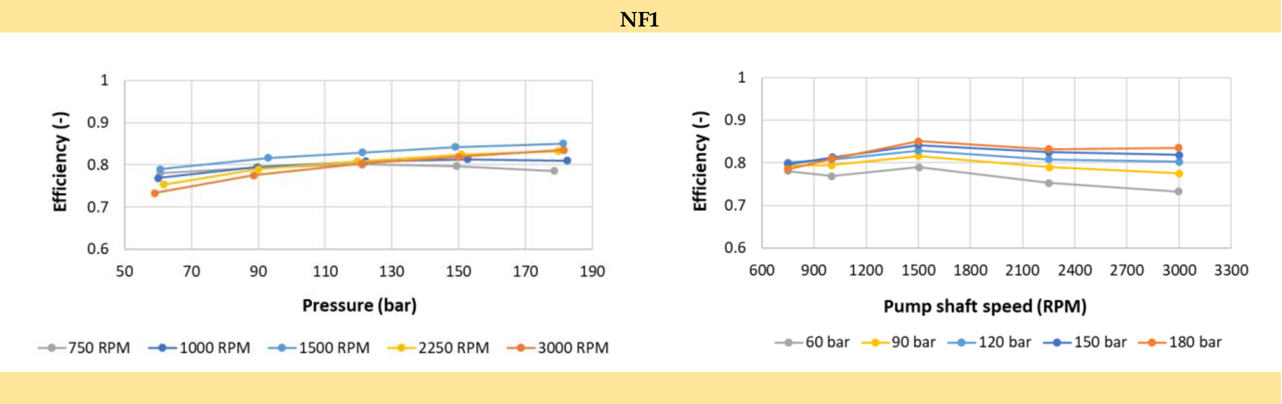


FIGURE 4: **EFFICIENCY TRENDS – Reference Fluid**



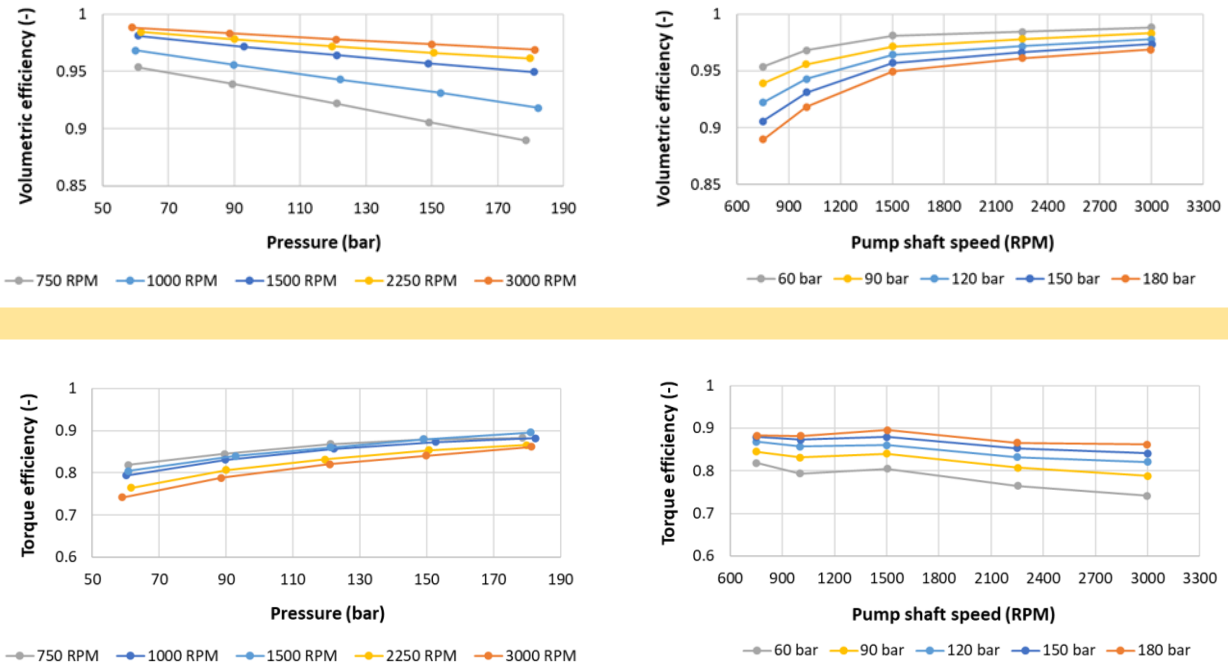
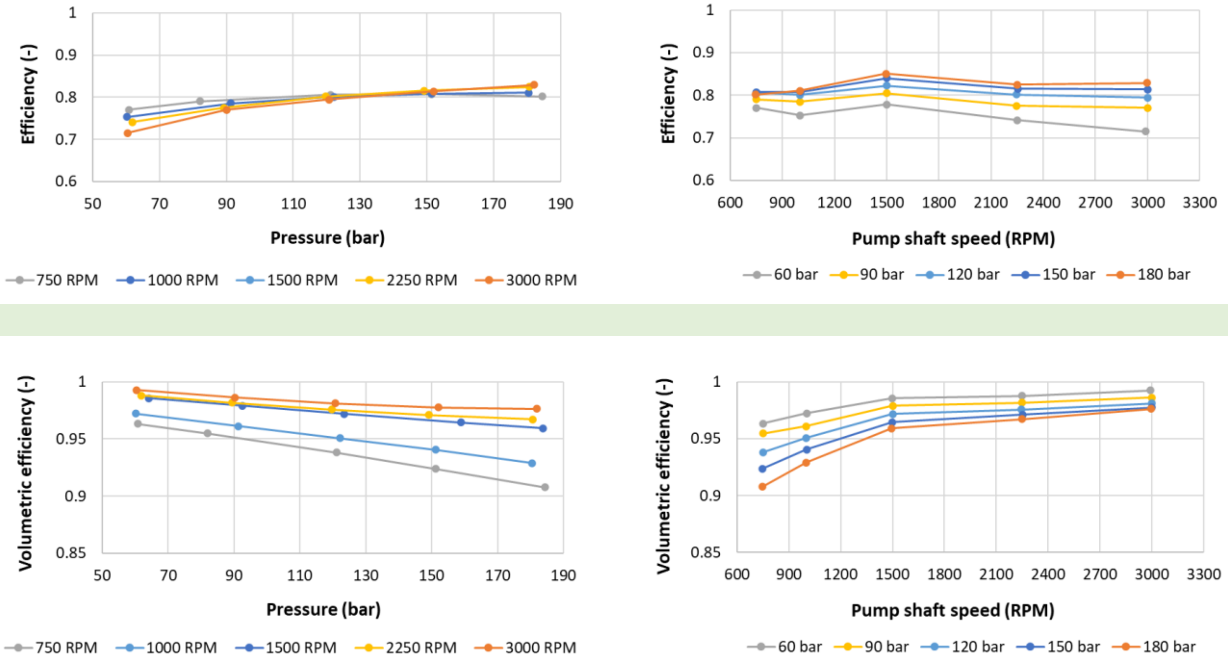


FIGURE 5: **EFFICIENCY TRENDS – Nanofluid 1**

NF2



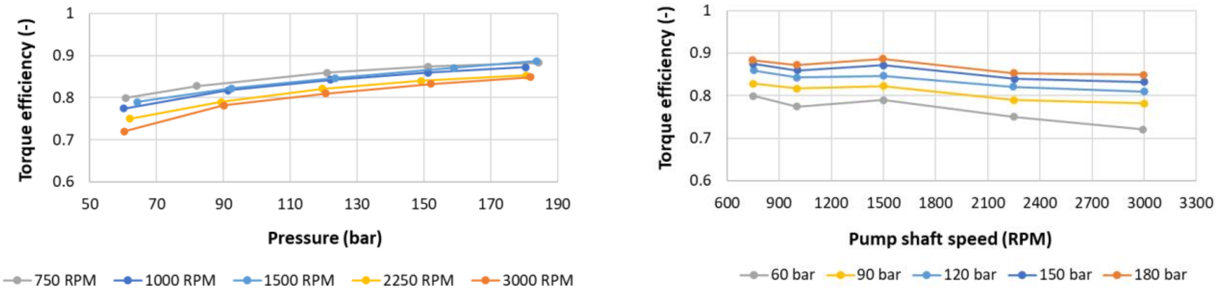


FIGURE 6: **EFFICIENCY TRENDS – Nanofluid 2**

CONCLUSION

The influence of Graphene-based nanofluids on the performance of an external gear pump is experimentally investigated, providing new information in the field. Two types of nanofluid are tested, prepared with the same base fluid and different concentrations of graphene nanoparticles (0.1% and 0.5% by mass). The pump performance is found to be influenced by the nanofluids and dependence on graphene concentration is found. The influence of the nanofluids on torque efficiency shows off through two effects. The former is their capability to clearly affect the torque loss sensitivity to pump speed. In fact, around 1000 RPM, where maximum torque-performance is obtained with the reference fluid, a relative minimum point is instead observed with nanofluids; with both nanofluids, the relative maximum point moves at a higher speed, around 1500 RPM. This suggests that the nanoparticles significantly affects the lubrication regime, pointing out its potential influencing the mechanical-hydraulic losses of the pump. Nanoparticle concentration does not affect the shift of the maximum of torque efficiency, but it does affect the whole torque efficiency level. At 0.1 % concentration, a slight performance decay is found. Al 0.5% concentration the effect is more evident. Concerning volumetric efficiency, nanofluids bring appreciable benefits at low speeds. This suggests that the nanofluid affects the hydraulic sealing phenomena. The nanofluid with the highest concentration of graphene brought the best benefits. The improvement is in the order of two percentage points.

The impact of the obtained results firmly promote further experimentation on hydraulic fluids containing graphene, exploring the chance to improve the performance of hydraulic components through the fine-tune of the fluid formulations. On the other hand, the results encourage to set up further research paths, aimed at the development of machines and components explicitly tailored to operate with graphene fluids.

REFERENCES

1. Müller, M.; Bartels, T.; Hedrich, K.; Wincierz, C.; Spikes, H. Tailor-made polyalkylmethacrylate additives to meet the stringent requirements of current and future generations of engine, transmission, gear and hydraulic oils. In Proceedings of the Annual Fuels and Lubes Asia Conference and Exhibition, 2007.
2. Fischer, F.; Murrenhoff, H.; Reinertz, O. Influence of additives on the friction behavior of hydraulic rod seals. *Olhydraulik und Pneumatik* **2016**, *2016-November*, 76-81.
3. Zhao, J.; He, Y.; Wang, Y.; Wang, W.; Yan, L.; Luo, J. An investigation on the tribological properties of multilayer graphene and MoS2 nanosheets as additives used in hydraulic applications. *Tribology International* **2016**, *97*, 14-20, doi:10.1016/j.triboint.2015.12.006.
4. Wang, H.; He, Y.; Fei, G.; Wang, C.; Shen, Y.; Zhu, K.; Sun, L.; Rang, N.; Guo, D.; Wallace, G.G. Functionalizing graphene with titanate coupling agents as reinforcement for one-component waterborne poly(urethane-acrylate) anticorrosion coatings. *Chemical Engineering Journal* **2019**, *359*, 331-343, doi:10.1016/j.cej.2018.11.133.
5. Ge, X.; Chai, Z.; Shi, Q.; Li, J.; Tang, J.; Liu, Y.; Wang, W. Functionalized graphene-oxide nanosheets with amino groups facilitate macroscale superlubricity. *Friction* **2023**, *11*, 187-200, doi:10.1007/s40544-021-0583-4.
6. Kinoshita, H.; Okamoto, T.; Hirai, Y.; Sugano, K.; Naohiro, M. Low Friction of Graphene Oxide Aggregates in Lubricant Oil between a Steel Ball and Glass Disk under Boundary Lubrication. *ACS Omega* **2022**, *7*, 40983-40989, doi:10.1021/acsomega.2c04181.
7. Ravishankar, H.; Moazzem, S.; Jegatheesan, V. Performance evaluation of A2O MBR system with graphene oxide (GO) blended polysulfone (PSf) composite membrane for treatment of high strength synthetic wastewater containing lead. *Chemosphere* **2019**, *234*, 148-161, doi:10.1016/j.chemosphere.2019.05.264.
8. Pandian, P.M.; Pandurangan, A. Flexible asymmetric solid-state supercapacitor of boron doped reduced graphene for high energy density and power density in energy storage device. *Diamond and Related Materials* **2021**, *118*, doi:10.1016/j.diamond.2021.108495.

9. Trasobares, J.; Martín-Romano, J.C.; Khaliq, M.W.; Ruiz-Gómez, S.; Foerster, M.; Niño, M.Á.; Pedraz, P.; Dappe, Y.J.; de Ory, M.C.; García-Pérez, J.; et al. Hybrid molecular graphene transistor as an operando and optoelectronic platform. *Nature Communications* **2023**, *14*, doi:10.1038/s41467-023-36714-7.
10. Liu, Y.; Yu, S.; Shi, Q.; Ge, X.; Wang, W. Graphene-Family Lubricant Additives: Recent Developments and Future Perspectives. *Lubricants* **2022**, *10*, doi:10.3390/lubricants10090215.
11. Wang, L.; Tieu, A.K.; Hai, G.; Li, J.; Zhu, H.; Sang, T.P.; Yang, J. Na2CO3 and graphene nanocomposites toward efficient lubrication. *Carbon* **2021**, *177*, 138-150, doi:10.1016/j.carbon.2021.02.074.
12. Liu, Y.; Ge, X.; Li, J. Graphene lubrication. *Applied Materials Today* **2020**, *20*, doi:10.1016/j.apmt.2020.100662.
13. Zhao, Z.; Fan, X.; Li, Y.; Zeng, Z.; Wei, X.; Lin, K.; Zhu, M. Well-dispersed graphene toward robust lubrication via reorganization of sliding interface. *Journal of Industrial and Engineering Chemistry* **2023**, *119*, 619-632, doi:10.1016/j.jiec.2022.12.008.
14. Peng, Y.; Wang, C.; Zhu, Z.; Tang, W.; Wang, D.; Lu, H. Anti-Friction Properties of Modified Graphene Oxide Lubricants for Wire Rope in a Mine Hoist. *Mocaxue Xuebao/Tribology* **2021**, *41*, 149-159, doi:10.16078/j.tribology.2020135.
15. Cai, T.; Liu, D.; Liu, S. Fluid-like graphene oxide organic hybrid materials as efficient anti-wear and friction-reducing additive of polyethylene glycol. *Tribology International* **2021**, *159*, doi:10.1016/j.triboint.2021.106880.
16. Zhao, J.; Wang, Y.; Wang, W.; He, Y.; Luo, J. An investigation on tribological properties of graphene and M0S2 nanoparticles as additives in aviation hydraulic oil. In Proceedings of the Society of Tribologists and Lubrication Engineers Annual Meeting and Exhibition 2015, 2015; pp. 433-439.
17. Kader, A.; Selvaraj, V.; Ramasamy, P.; Senthilkumar, K. Experimental investigation on the thermo-physical properties and tribological performance of acidic functionalized graphene dispersed VG-68 hydraulic oil-based nanolubricant. *Diamond and Related Materials* **2023**, *133*, doi:10.1016/j.diamond.2023.109740.
18. Li, X.; Gan, C.; Han, Z.; Yan, H.; Chen, D.; Li, W.; Li, H.; Fan, X.; Li, D.; Zhu, M. High dispersivity and excellent tribological performances of titanate coupling agent modified graphene oxide in hydraulic oil. *Carbon* **2020**, *165*, 238-250, doi:10.1016/j.carbon.2020.04.038.
19. Yan, L.; Li, X. Effect of Modified Graphene on Tribological Properties of Hydraulic Oil. *Petroleum Processing and Petrochemicals* **2020**, *51*, 76-81.
20. Sepehrnia, M.; Shahsavar, A.; Maleki, H.; Moradi, A. Experimental study on the dynamic viscosity of hydraulic oil HLP 68- Fe3O4-TiO2-GO ternary hybrid nanofluid and modeling utilizing machine learning technique. *Journal of the Taiwan Institute of Chemical Engineers* **2023**, *145*, doi:10.1016/j.jtice.2023.104841.