A Flow Control System for a Novel Concept of Variable Delivery External Gear Pump

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Abstract

This paper describes a novel concept for a low cost variable delivery external gear pump (VD-EGP). The proposed VD-EGP is based on the realization of a variable timing for the connections of the internal displacement chambers with the inlet and outlet ports. With respect to a standard EGP, an additional element (slider) is used along with asymmetric gears to realize the variable timing principle. Previously performed tests confirmed the validity of the concept, for a design capable of varing the flow in the 65%-100% range.

Although the VD-EGP concept is suitable for various flow control system typologies (manual, electro-actuated, hydraulically flow- or pressure- compensated), this paper particularly details the design and the test results for a prototype that includes both a manual flow control system and a pressure compensator. Flow vs pressure and volumetric efficiency curves are discussed along with transient (outlet flow fluctuation) features of the VD-EGP.

KEYWORDS: Variable Displacement Pump, Variable Flow Pump, External Gear Pump

1. Introduction

External gear pumps (EGPs) are widely used in several fluid power applications due to their reliability, low cost, high compactness, good efficiency, good tolerance to contaminants and cavitation. However, the classic EGP design (Fig. 1) is inherently fixed displacement, consequently generation of flow “on demand” cannot be achieved unless controlling the shaft speed. This has limited the diffusion of inexpensive EGPs to modern and high energy efficient hydraulic machines, which are based on architectures layouts that requires variable displacement hydrostatic units. This limitation has driven the effort of many researchers from both academia and industry for formulating variable displacement solutions based on the external gear design. The several different solutions that have been proposed can be broadly categorized in two sets. The first set is given by the solutions that change the meshing length of the gears (through relative axial motion between the gears), like those described in /1,2,3,4/. The second set of ideas is based on variation of the interaxis of operation of the gears, as described for example in /5,6/. However, none of these solutions has encountered successful commercialization for high pressure applications due to the major issues related to the implementation of movable gears in an EGP design: sealing of the displacement chamber, achieving proper power transmission between the gears, obtaining a good balance of the internal parts for all operating conditions. For these reasons, these solutions can be implemented with reasonable cost and performance only for low pressure applications, such as the automotive application documented in /7/.

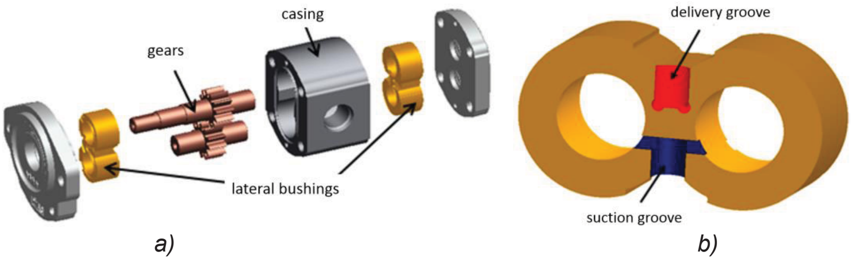


Figure 1: Pressure compensated EGP: exploded view (*a*), lateral bushings (*b*)

The authors' have proposed a different concept for variable delivery (VD) EGP that preserves all advantages of traditional EGPs. The novel concept, which will be described in §2, is based on the realization of a variable timing for the connections of the tooth space volumes (TSVs) with both the inlet and the outlet. The solution does not require axial or radial motion of the gears, and for this reason is suitable for high pressure applications. The basic idea was first presented in /8/: in this work a proper design of the gears was presented to permit a flow variation range in the 68-100% interval. Simulation results and proof of concept tests were also discussed to show the potentials of the solution. In /9/, the authors showed that a higher range of flow variation could be achieved by varying the design of the gears.

In this work, a working prototype of the VD-EGP that utilizes the same gears introduced in /8/ is described. The architecture chosen for the flow control system, described in §3, implements in a single device both the manual control of the flow and the pressure limiter, which reduces the displacement only if a certain set pressure is reached at the pump outlet. The last §4 is dedicated to the discussion of the experimental results obtained by the prototype, as concerns steady-state performance and outlet pressure fluctuations.

2. Description of the VD-EGP

The VD-EGP realizes a variation of the timing of the connections of the TSVs with the inlet/outlet lateral grooves machined in the lateral bushings. This timing variation is achieved with the introduction of a single-axis movable element, the *slider* in Fig. 2.

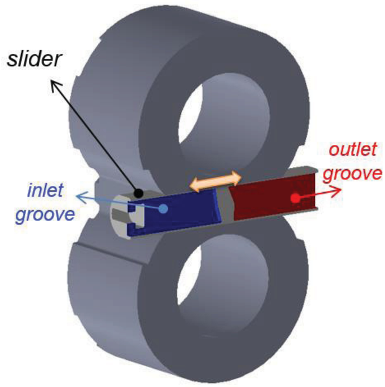


Figure 2: Slider in the bearing block

The position of the slider, which could be also placed in the pump casing for a non-pressure compensated EGM, determines the amount of flow displaced by the unit per revolution of the shaft. In order to understand the mechanism of operation of the VD-EGP, the displacing action for an EGP is shown in Fig. 3. In Fig. 3*a*, a reference TSV is highlighted; in Fig. 3*b*, the TSV volume is plotted as a function of the shaft angle.

The displacement of the fluid in the EGP occurs in the angular interval θ, which defines the meshing region. Within this angular interval, there is a sub-interval in which the TSV is trapped between points of contact. The limits of this subinterval are indicated with D and S, which normally (if the contact occurs in the involute part of the tooth) lies on the line of action. In the region D-S, the displacing action is permitted by the inlet/outlet grooves machined in the bearing block (the trace of the grooves is represented in Fig. 3*a*). In a standard EGP, the commutation of each TSV from the outlet to the inlet is realized when the volume is minimum (point M in Fig. 3*a*), so that the max volumetric capacity of the pump is utilized. Nevertheless, a small degree of cross-porting will be necessary to obtain an optimal performance in terms of minimizing internal pressure peaks, cavitation and fluid borne noise emissions /10,11/.

In the proposed VD-EGP, the slider (Fig. 2) is capable of a single degree of motion as represented by the arrow; hence, it can vary the position of these grooves affecting the angular position at which the commutation between the connections of each TSV with the inlet/outlet ports occur. If the slider is positioned at a different location, the inlet/outlet commutation of each TSV occurs at a location different than M, thus a different net flow is displaced by the unit. It is important to notice that this concept is valid only if the commutation point is established by the slider in the angular region D-S; outside this range the slider would realize a direct bypass connection between the inlet and outlet port through the gear depth, being the volume not trapped between contact points.

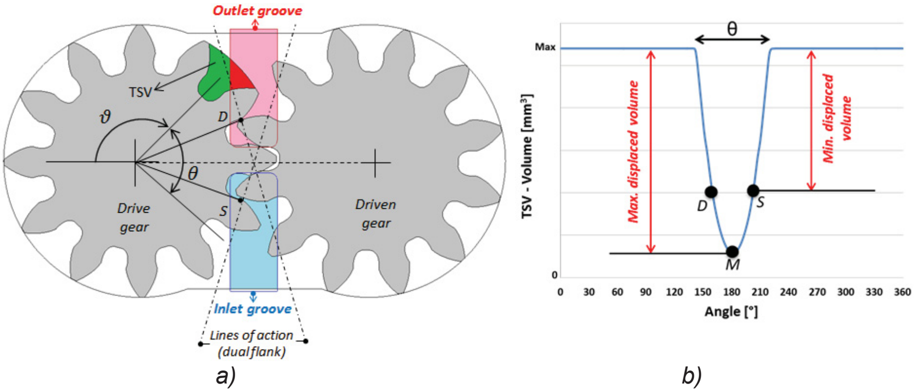


Figure 3 – a) Displacing action for a dual flank EGP; b) TSV volume variation

More details on this concept are described in /8/. In particular, in this work it is detailed the difficulty of achieving a high flow variation range with conventional gear profiles, due to the proximity of the location of points D and S with point M (Fig. 3). For this reason, an unconventional asymmetric tooth profile was chosen, and a numerical optimization procedure based on the software HYGESim (HYdraulic GEar machines Simulator, /12/) was used to define the optimal tooth profile along with the shape of the grooves to be machined in the slider. In /8/, the authors also presented experimental results obtained from a prototype EGP that used the new gears and two alternative shapes for the grooves machined in the lateral bushings (Fig. 1): one for the maximum flow (100%) and one for the minimum flow (68%). These results permitted not only the validation of the numerical approach, but also showed the potentials of the approach for efficiently the flow of an EGP; in fact a torque reduction in the same order of the flow reduction was observed from all the performed tests. These promising results motivated the following research step aimed at designing an actual prototype that includes a flow actuation system.

3. VD-EGP Prototype

The gears and the slider grooves shape optimized in /8/ were used in this work to implement a fully operational prototype of the VD-EGP. The rationale behind the chosen design for the prototype can be summarized by following points:

- Opportunity of adding the flow regulation system to an existing commercial unit. In this way it can be shown that the VD-EGP could potentially be considered as an add-on feature for commercial pump. This also permitted to reduce the manufacturing cost of the prototype, since the case, the covers and the bearings are those of the existing commercial unit. The commercial unit chosen was an 11.2 cm^3/rev CASAPPA PL 20.

- Need of testing the pump operation for well-defined fixed positons for the slider (manual control of flow rate).

- Demonstrate the easiness of implementing hydraulically compensated strategies for the flow regulation system. The case of a pressure compensator (or pressure limiter) was chosen.

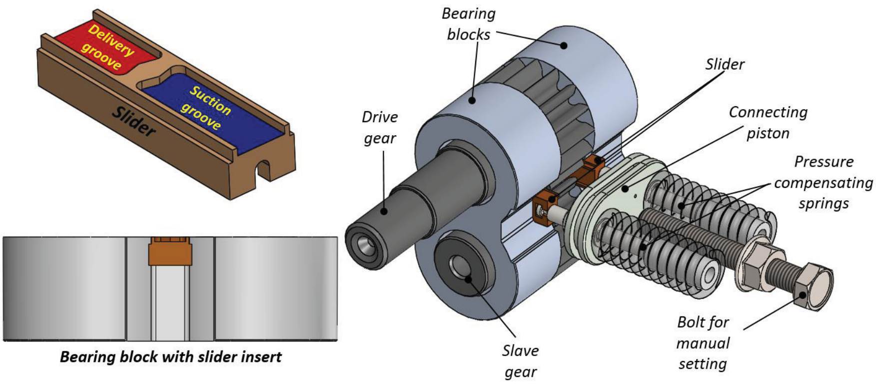


Figure 4 – Slider and its placement on the bearing block (left), complete flow control system (right)

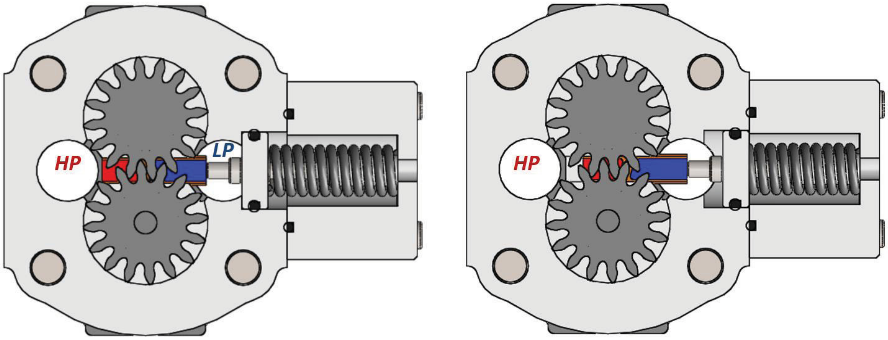


Figure 5 – Operation as pressure compensator: max flow (left) min flow (right)

The Figs. 4 and 5 show the implementation of the flow regulation system on the existing pump: in particular, Fig. 4 shows the different elements used to accomplish both the function of manual adjustment of the flow as well as functioning as pressure compensator. An adjustable bolt is used to force the slider at specific locations (manual setting). In case the bolt is removed or placed far away from the connecting piston (Fig. 4), the operation as pressure compensator is achieved. This operating mode is illustrated in Fig. 5: the delivery pressure acts at one side of the slider, against the spring force. The setting for the spring force used for the VD-EGP in this work was 100 bar.

End stops can be used to limit the position of the slider within the max and min flow range. However, the min flow range end stop can be removed to enable the functioning as pressure relief. In fact, if the slider is moved beyond the min flow position, a bypass flow is established between the outlet and inlet port. For the proposed VD-EGP prototype, the overall slider displacement, to achieve the full flow variation range, is about 6 mm. This displacement range is sufficient for achieving good sensitivity for both the actuation systems considered in this work.

The actual implementation is shown in the picture of Fig. 6.

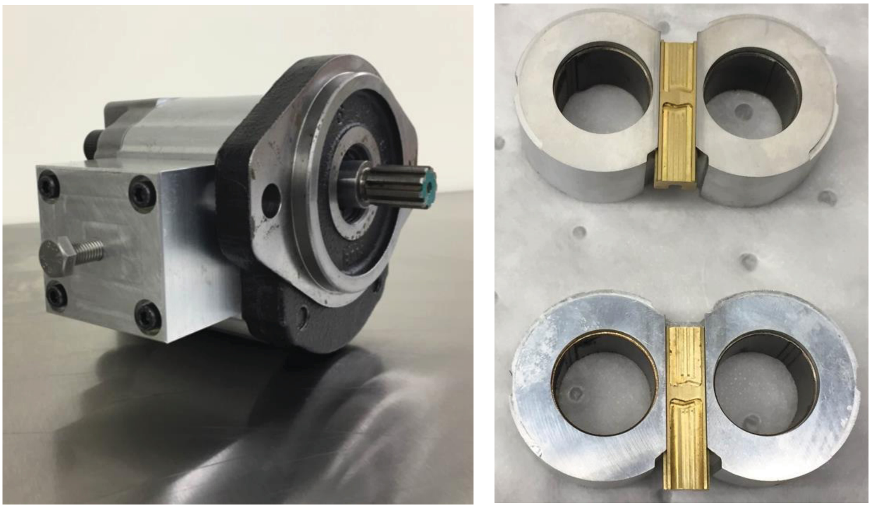


Figure 6 – Picture of the VD-EGP prototype. Details on the lateral bushings

4. Test Results

The VD-EGP of Fig. 6 was tested at the Maha Fluid Power Research Center in accordance with ISO 4409, with the circuit of Fig. 7. An ISO VG46 oil was used for the tests, at a controlled temperature of 50˚C. Before performing the tests, the pump case was broken-in by using the commercial gears. This slighlty penalizes the optimal radial (at tooth tip) sealing of the VD-EGP, however prototype gears couldn't be used because they were not properly heat treated.

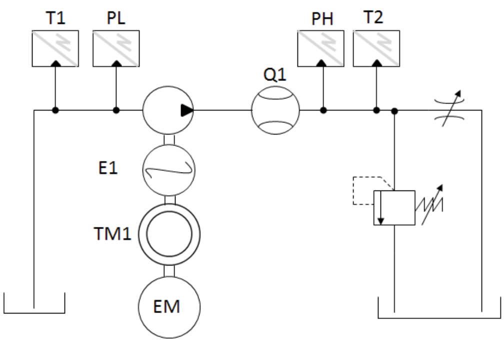


Figure 7 – Hydraulic circuit used for the pump characterization

4.1. Performance of VD-EGP with Manual Setting

By setting the adjustable bolt of Fig. 4 in several positions, it was possible to test the VD-EGP prototype in different positions. Three different settings were chosen for plotting the experimental results in Figs. 8 and 9: 100%, 84% and 68% of maximum flow.

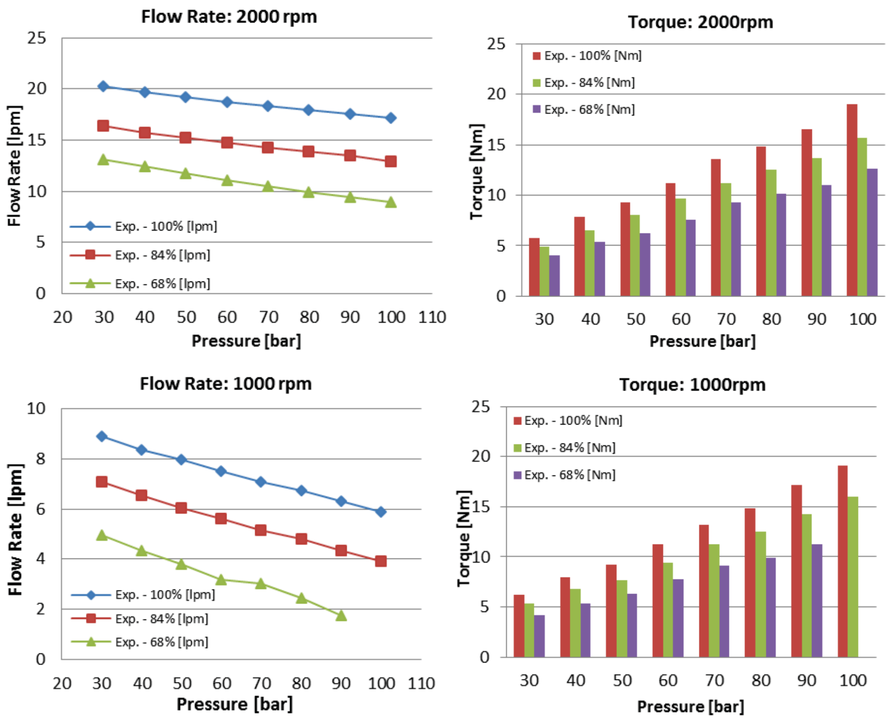


Figure 8 – Operation as pressure compensator: max flow (left) min flow (right)

Figure 8 shows the flow rate vs. pressure and the shaft torque vs. pressure for 1000 rpm and 2000 rpm. The maximum pressure during the test was limited to 100 bar due to the absence of final hardening process on the gears, which would bring the VD-EGP to operate up to 250 bar as the commercial unit taken as reference. The torque plots demonstrate that the shaft torque reduces with the displacement. This is in accordance to the VD-EGP variable timing operating principle, which keeps the TSV pressurized for a longer time during the meshing process, thus decreasing the torque request /8/.

The flow rate plots of Fig. 8 point out a significant decrease in flow rate at a given setting for the slider due to volumetric losses. In terms of volumetric efficiency, this effect can be shown in Fig. 9.

Due to the fact that radial leakages (at the tip of teeth) as well as axial leakages (at the lateral side of gears) ideally do not vary with the slider position, it is expected

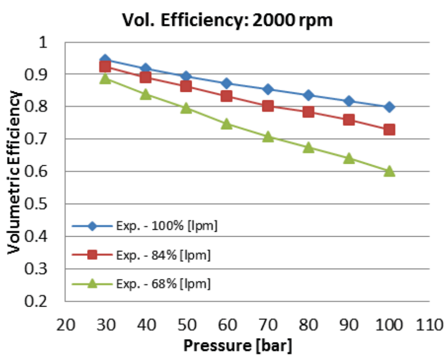
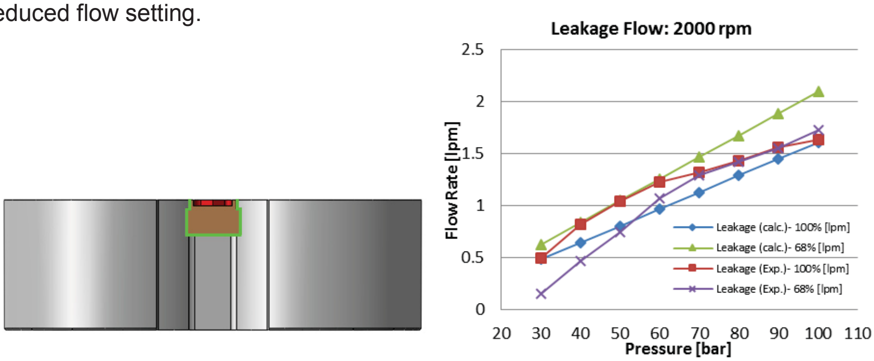


Figure 8 – Volumetric efficiency of

a reduction of volumetric efficiency at reduced flow setting.

the VD-EGP prototype



a) *b)*

Figure 9 – Additional leakages introduced by the slider

Reasons for efficiency levels lower than a conventional EGP are the imperfection of the gears (realized with a wire electric discharge machining process) and the break-in process used for the VD-EGP prototype described above. However, this do not explain the rapid decrease of volumetric efficiency with pressure which was not observed in the proof of concept tests described in /8/, which utilized the same gears and similar pump case described but in absence of the slider and flow regulation system. In order to better understand source of additional volumetric losses in the VD-EGP prototype, the results of Fig. 8 and the similar one from the proof of concept tests of /8/ were used to derive the additional leakages introduced by the apparatus of Figs. 4 and 5. These results are reported in Fig. 9*b*, as “exp.” curves; “calc.” curves indicates the results of the Poiseuille’s eq. for the leakages at the slider surfaces (in green in Fig. 9*a*):

$$Q_{leak} = \frac{h^3}{12 \cdot \mu} \cdot \frac{\Delta p}{L} \cdot b \qquad (1)$$

Where, h is the gap height, L is the gap length (which depends on the slider position), b is the gap width and Δp is the difference in pressure across the gap. The comparison between the two trends of Fig. 9 shows how the additional reduction of volumetric efficiency – respect to what expected for a standard EGP, is essentially due the green leakage path of Fig. 9*a*. Two important considerations can be derived from the result of Fig. 9*b*:

- The flow control system of Fig. 4, and in particular the slider, didn’t compromise the axial or radial balance of the gears, since additional leakages are only due to the bypass path created by the slider
- The leakages for the VD-EGP could be significantly reduced in case of: a) a lower clearance between the slider and its seat on the bushing were used (the value

obtained for the prototype was higher than a typical clearance of a spool valve); b) a simplified different of the VD-EGP that uses only one slider were used. In fact, only for long gears it would be necessary to use a dual-slider design as the one shown in Fig. 4; c) a seal were introduced between the slider and its seat on the bushings. All these three options are taken into account for the creation of a future VD-EGP high efficient prototype.

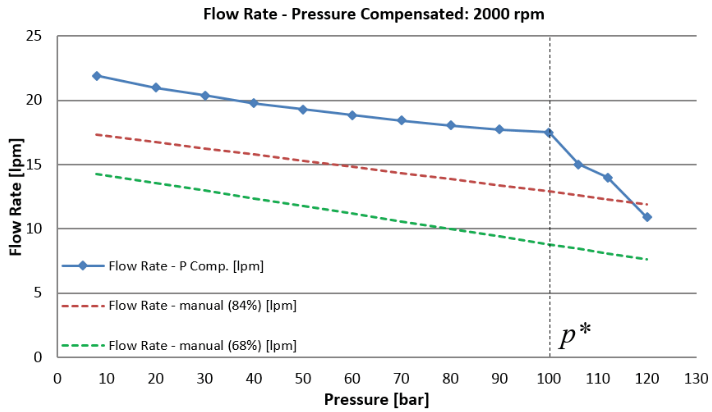


Figure 10 – Tests on VD-EGP (pressure compensator): flow rate vs. pressure

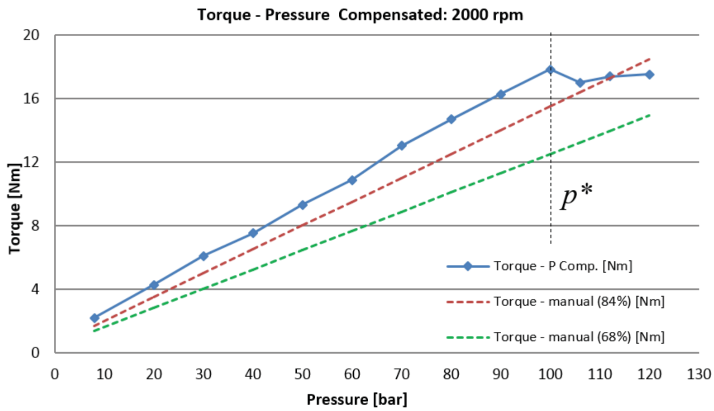


Figure 11 – Tests on VD-EGP (pressure compensator): torque vs. pressure

4.2. Performance of VD-EGP with Pressure Compensator

The operation of the VD-EGP with the pressure compensator was tested using the same test circuit of Fig. 7. Measured flow rate vs. pressure characteristic is shown in Fig. 10 (blue curve). The characteristic resembles the 100% flow curve of Fig. 7 until the pressure reaches the setting p^*. For higher pressure, the flow reduces without requesting for additional torque, as shown in Fig. 11. The dotted lines in both Figs. 10 and 11 show the characteristics achieved by the measurements of §4.1.

5. Conclusions

This paper presented a working concept for Variable Delivery External Gear Pump (VD-EGP), particularly focusing on the implementation of a prototype that includes the flow variation system. Two different actuation systems were considered: (1) a manual actuation system in which the user can set the level of output flow; (2) a pressure compensator that adjust the outlet flow when a specific pressure setting is reached.

The results focused on the measured steady-state features (flow rate and torque vs. pressure; volumetric efficiency) of the VD-EGP prototype, and demonstrate the validity of the concept for efficiently varying the flow displaced by an external gear machine without compromising the key features of low cost and limited number of parts. Essentially, the VD-EGP design is based on the introduction of a slider at the lateral side of the gears of a traditional EGP, and this can be successfully implemented for both high pressure and low pressure applications. The VD-EGP prototype discussed in this work show the case of a high pressure design (up to 250 bar), although during the experiments the max pressure was limited to 120 bar due to the absence of proper treatment on the gears. The results highlight the design challenge related to the additional leakages introduced by the slider, and possible solutions that will be considered in future VD-EGP development are discussed.

The future work will also focus on more aggressive modification of the gears profile, to achieve a higher range of efficient flow variation.

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8. Nomenclature

L	Gap lenght	mm
Q_{leak}	Leakage Flow	L/min
b	Gap width	mm
h	Gap height	mm
p^*	Spring set pressure	bar
μ	Fluid viscosity	Pa·s

Abbreviations

EGP	External Gear Pump
TSV	Tooth Space Volume
VD	Variable Delivery