ISSN 1454 - 8003
Proceedings of 2022 International Conference on Hydraulics and Pneumatics - HERVEX
November 9-10, Băile Govora, Romania

EXPERIMENTAL RESEARCH ON EQUIPPING LOW-PRESSURE PUMPING UNITS WITH MINIBOOSTERS

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Abstract: *One of the effective methods of achieving high pressures in hydraulic drive systems is to equip low-pressure pumping units with minibooster-type hydraulic pressure intensifiers. These hydraulic devices, with pulsating mode of operation, consume low-pressure high flows rates to generate high-pressure low flow rates. This is why low-pressure pumping units equipped with miniboosters are used to generate high pressure rates in constant confined volumes or when moving hydraulic cylinders with heavy loads, over long distances and at low speed rates. Through experimental tests, carried out on a bench dedicated to the topic of this paper, the authors of the material comparatively analyse the displacement of a hydraulic cylinder, with constant load of 800 bar over the entire advance stroke, when the pumping unit that supplies the cylinder is equipped, successively, with three types of miniboosters.*

Keywords*: Low-pressure pumping unit, minibooster, high pressure, hydraulic cylinder*

1. Introduction

There are known two solutions for generating high pressure in hydraulic drive systems: an expensive one, based on pumps and equipment for adjusting / controlling high pressure hydraulic parameters, and a cheaper one, based on pumps and equipment for adjusting / controlling low pressure hydraulic parameters, plus hydraulic pressure intensifiers. For example, Fig. 1 shows the two drive solutions for a hydraulic cylinder with a 700-bar load.

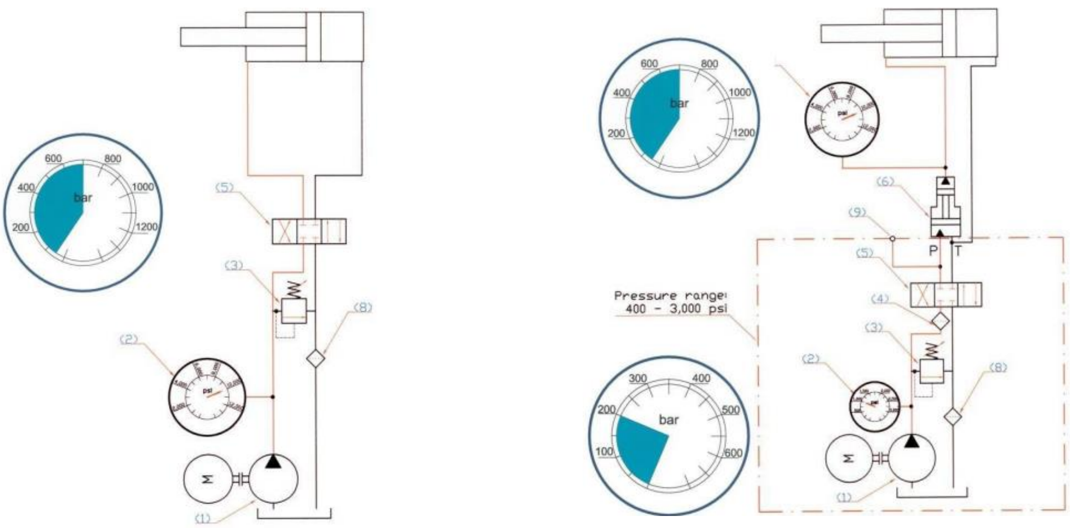

Fig. 1. Generating 700-bar pressure for actuating a hydraulic cylinder: ***left side*** - with high-pressure pump; ***right side*** - with low-pressure pump and hydraulic pressure intensifier

In the hydraulic drive diagram [1] shown in Fig. 1-left side, motor **M** drives **high-pressure pump (1)**, to direct hydraulic oil, at a pressure of 700 bar, indicated on pressure gauge **(2)**, limited by pressure control valve **(3)**, via directional control valve **(5)**, switched to the field of parallel arrows, to the

cylinder rod chamber. The cylinder piston chamber discharges into the tank via return filter **(8)**, and the hydraulic cylinder moves to the right with a 700-bar load.
One can move the same hydraulic cylinder to the right, with a 700-bar load, according to the hydraulic drive diagram [1] shown in Fig. 1-right side, where **low-pressure pump (1)**, pressure control valve **(3)** and directional control valve **(5)** operate at 200 bar, indicated on pressure gauge **(2)**. Return filter **(8)** remains, while additional low pressure filter **(4)** and **pressure intensifier (6)** appear; the latter is fed via connecting fitting **P**, from the primary side, by pump **(1)**, and on the outlet of the secondary side, it delivers hydraulic oil at 700 bar in the cylinder rod chamber. Due to the pulsating mode of operation of the pressure intensifier, one uses this drive diagram for **short displacements under load** of the hydraulic cylinders or with the purpose of **achieving and maintaining the load at the stroke end**.
State of the art in the field of technical applications for the use of low-pressure pumping units equipped with oscillating hydraulic pressure intensifiers (miniboosters) does not include applications with displacements of hydraulic cylinders that have high loads over the entire stroke. ***The aim*** of this paper is to demonstrate experimentally the possibilities of using miniboosters in such applications, too, with reasonable limits of uniformity and continuity of displacement of the actuated cylinders, as well as the possibilities of equipping the same low-pressure pumping unit with miniboosters with different amplification factors, depending on the type of application in which it is used.

2. Materials and Methods

To achieve the proposed goal, the authors have used an experimental method by which they have monitored the dynamic behaviour of a hydraulic cylinder which, being fed into the piston chamber by a minibooster, moves with a constant load, equivalent to a pressure of **800 bar**, over the entire stroke. The minibooster has been integrated into a low-pressure pumping unit, and the hydraulic cylinder under testing - in a test bench. Three sets of tests have been performed, one for each of the miniboosters [2] shown in figure 2 and table 1.

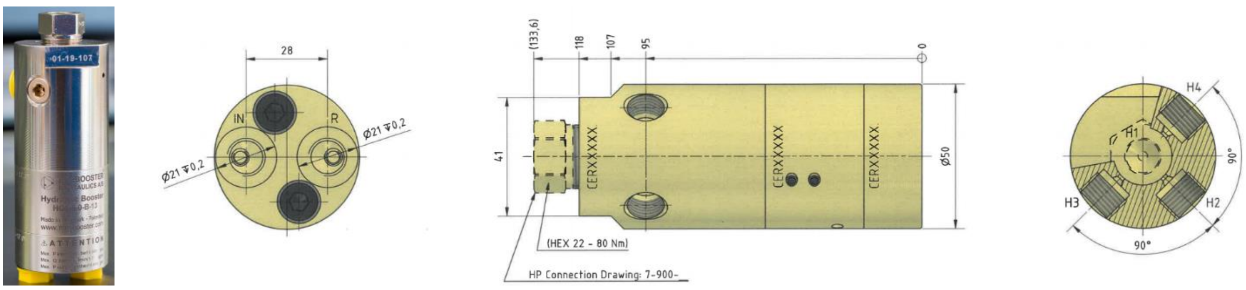

Fig. 2. HC7 miniboosters [2]

Table 1: Technical features of the miniboosters used in the set of three tests

Minibooster technical features	**Minibooster code**		
	HC7-5.0-B-12	**HC7-6.6-B-12**	**HC7-7.6-B-12**
Low pressure connecting fittings: **IN** (inlet) / **R** (return)	1/4" BSPP	1/4" BSPP	1/4" BSPP
High pressure connecting fitting **H1** (p_{HP})	M22 x 1.5	M22 x 1.5	M22 x 1.5
High pressure connecting fitting **H2** (p_{HP})	9/16-18 UNF	9/16-18 UNF	9/16-18 UNF
Amplification factor **$i = p_{HP} / p_{IN}$**	5.0	6.6	7.6
Maximum inlet flow rate: **$Q_{max\ IN}$** [l/min]	14	13	13
Maximum outlet flow rate: **$Q_{max\ H1}$** [l/min]	1.6	1.3	1.1

Note:
Because the actual flow rate **$Q_{max\ IN}$** supplied by the low-pressure pumping unit (***10.5 l/min***) is less than the values in table1, the flow rates **$Q_{max\ H1}$** will have lower values as well.

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2.1 Low-pressure pumping unit equipped with minibooster

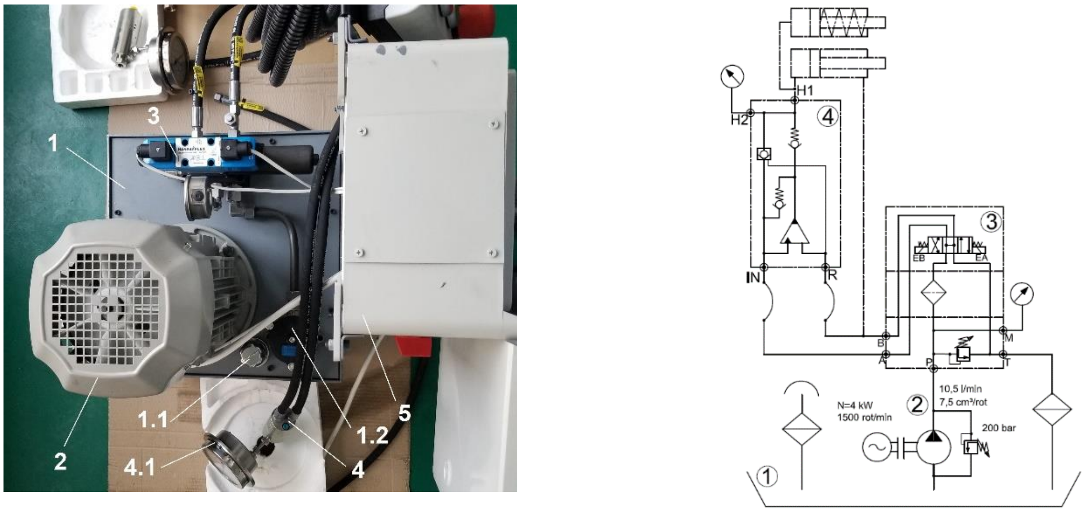

Fig. 3. Low-pressure pumping unit equipped with minibooster:
left side - overview; ***right side*** - hydraulic schematic diagram

The pumping unit in figure 2 comprises: **1**= oil tank (38 l volume); **1.1**= fill and vent filter; **1.2**= return filter; **2**= low-pressure electric pump (4 kW; 1500 rev/min; 7.5 cm^3/rev; 250 bar); **3**= block with hydraulic devices (pressure control valve; pressure filter; 4/3 hydraulic directional control valve, Dn6, electrically actuated; 250-bar pressure gauge); **4**= HC7 minibooster (technical features as in table 1); **4.1**= 2500-bar pressure gauge; **5**= electric panel.
Pressure adjustment on the circuit **H1**, which supplies the hydraulic cylinder actuated by the pumping unit, is done using the pressure control valve on the hydraulic block of the unit, and the adjusted value of this pressure can be read on the high pressure gauge, mounted in the connecting fitting **H2.**

2.2 Test bench for low-pressure pumping unit equipped with minibooster

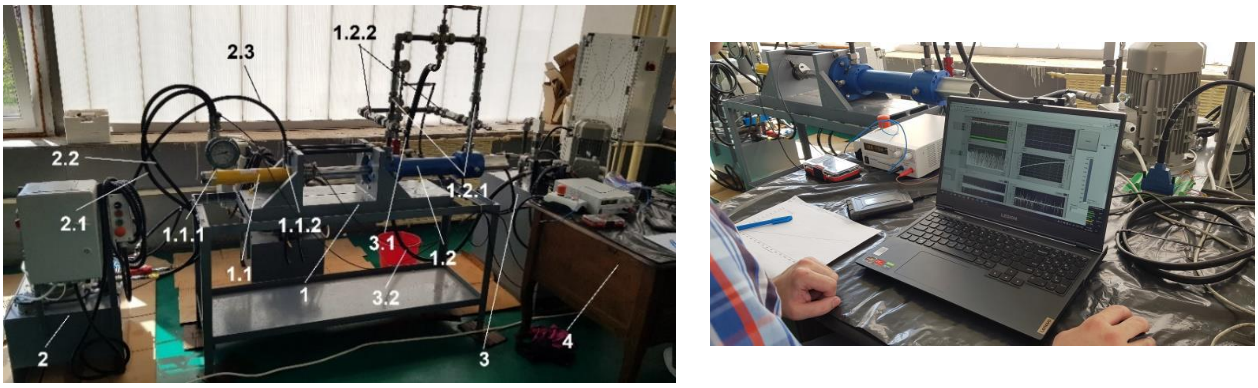

Fig. 4. Test bench for pumping unit equipped with minibooster

The structure of the test bench [3, 4] and the pumping unit in figure 4 is as follows:
1: Module for clamping the hydraulic cylinders; **1.1**: test cylinder with piston Ø= 38.1 mm, rod Ø= 25 mm, stroke length= 257 mm, p_{max}= 700 bar; **1.1.1**: fitting that connects cylinder piston chamber with secondary side of the minibooster; **1.1.2**: connecting fitting and hose for cylinder rod chamber; **1.2**= load cylinder with built-in stroke transducer and piston Ø= 80 mm, rod Ø= 45 mm, stroke length= 300 mm, p_{max}= 300 bar; **1.2.1**= cylinder chambers inlet check valves; **1.2.2**= cylinder chambers outlet check valves;
2: Low-pressure pumping unit (previously presented); **2.1, 2.2**= hoses connecting the primary side of the minibooster to the consumers of the hydraulic directional control valve of the unit;

3: Pumping station for filling the load cylinder equipped with: 2-kW, 10-bar, and 90-l/min electric pump; oil tank with V= 180 l; filling pressure control valve; proportional pressure control valve (acting as load); fill and vent filter; return filter; **3.1**= cylinder chambers fill fitting and hose; **3.2**= cylinder chambers drain fitting and hose;
4: Control and data acquisition module (figure 4 - right side) acquiring data from the transducers of: minibooster primary side pump pressure (**p1**); load cylinder pressure (**p2**); filling pump pressure (**p3**); minibooster primary side input flow rate (**Q1**); load cylinder flow rate (**Q2**); **stroke** (built into the load cylinder).

2.3 Test conditions

- Adjusted pressure at the safety valve of the pumping unit: $\mathbf{P_r = 190}$ **bar**;
- Adjusted pressure in the load cylinder: **800 bar** (potentiometer adjustment value for load cylinder compression = **50%**), for the test cylinder advance, and **20 bar** (potentiometer adjustment value for load cylinder extension = **0%**);
- 3 sets of tests have been made, with the same load, one for each of the three miniboosters, item no. 2 in figure 5, which successively equipped the tested low-pressure pumping unit;

Fig. 5. High-pressure test cylinder (1), powered by the minibooster (2) equipping the low-pressure pumping unit

- The displayed (acquired) load pressure is amplified by the following factors: **4.41** (for compression); **5.3** (for extension);
- The parameters measured using the transducers have been as follows: minibooster primary side pressure (denoted **P1** on graphs); load pressure equivalent to minibooster secondary side pressure (denoted **P2** on graphs); load cylinder filling pressure (denoted **P3** on graphs); minibooster primary side flow rate (denoted **Q1** on graphs); load cylinder flow rate (denoted **Q1** on graphs); load cylinder stroke (denoted **C** on the graphs).

3. Results and discussions

The following is the set of tests carried out for the pumping unit equipped with the minibooster with amplification factor i=5.0. At the end of the chapter, a comparison is made, by superimposition, between the time-variations of the displacement of the cylinders on the test bench, for the three cases of equipping a low-pressure pumping unit with miniboosters (i=5.0, i=6.6 and i=7.6).

3.1 Testing of the pumping unit equipped with minibooster, i=5.0

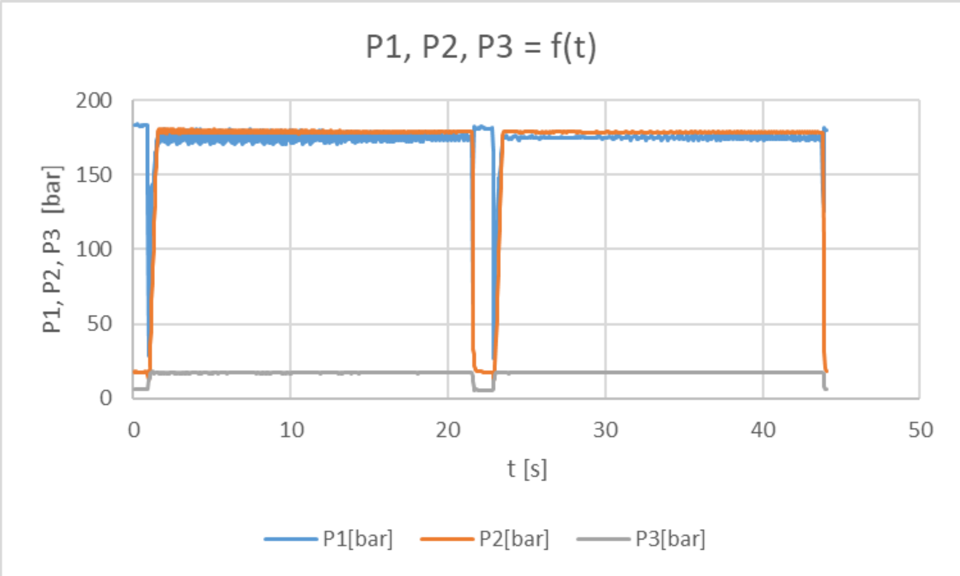

Fig. 6. Time-variation of pressures P1, P2, and P3

Figure 6 shows time-variations of the pressure in the minibooster primary side (P1), load pressure (P2) time-variations, and time-variations of the load cylinder filling pressure (P3), over two full strokes (extension + compression). On the first compression stroke, the P1 and P2 pressure pulsations are larger, because of the presence of air in the hydraulic circuits of the cylinders on the bench.

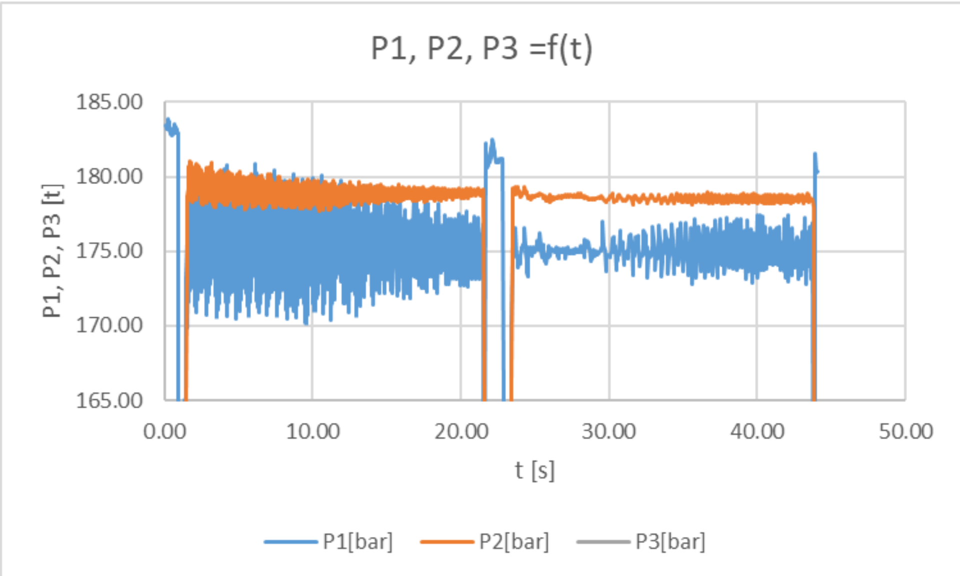

Fig. 7. Detail: time-variation of pressures P1 and P2

The detail in figure 7 shows the variations of pressures P1 and P2 [5], over two extension and compression strokes of the load cylinder. The detail has been made for the ***165-185 bar*** pressure range; this range that does not contain the pressure P3 variation, too. It is noted that the peaks of the pressures P1, ***183 bar*** roughly, are recorded when the direction of displacement of the load cylinder changes (transition from compression to extension), and equivalently the direction of displacement of the test cylinder changes (transition from advance stroke to retraction stroke).

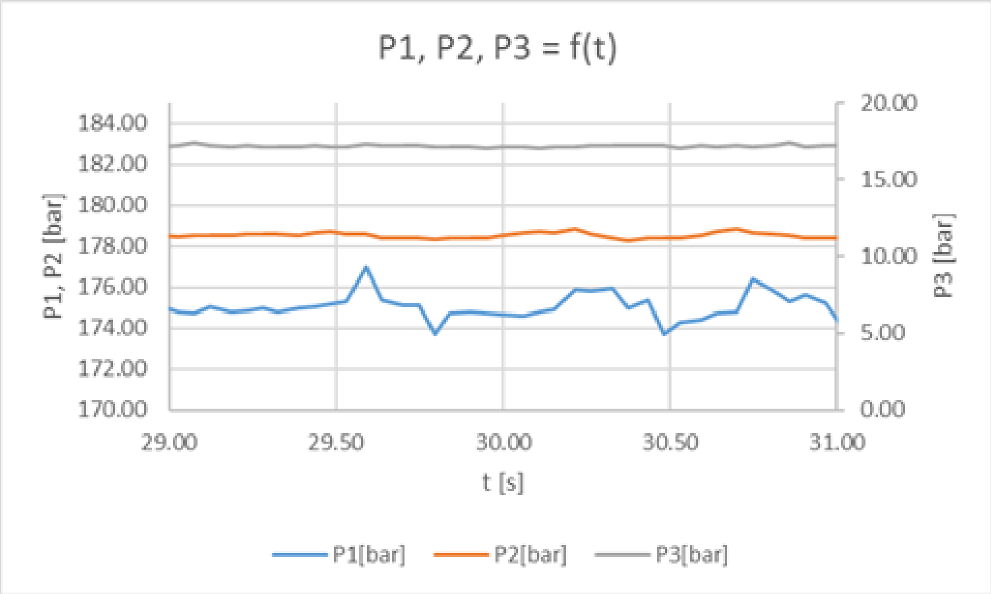

Fig. 8. Detail: time-variation of pressures P1, P2, and P3

The detail in figure 8 shows the variations of pressures P1, P2 and P3, over two compression strokes of the load cylinder. The detail has been made for a segment of the compression stroke of the load cylinder, corresponding to the ***29-31 s*** time range and the ***170-184 bar*** pressure range, for pressures P1 and P2, and the ***0-20 bar*** pressure range, for pressure P3.
One can notice that:
- Variation of the pressure in the minibooster primary (P1) is within the range ***174-177 bar***.
- Load pressure (that generates the resistive force of the test cylinder on the bench) variation is within the range ***178-179 bar***. Taking into account the ratio of the piston surfaces of the two cylinders on the bench, which is ***4.41***, this range becomes ***785-789 bar***.
- Variation of the load cylinder filling pressure is within the range ***17.5-18 bar***.

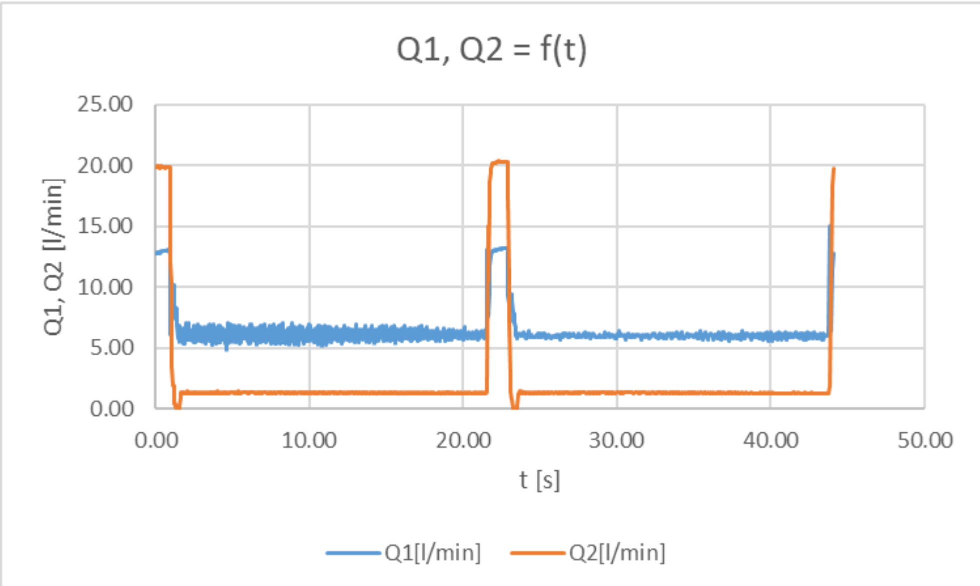

Fig. 9. Time-variation of flow rates Q1 and Q2

Figure 9 shows the time-variations of flow rates Q1 and Q2, over two full strokes of the load cylinder (extension + compression).

One can notice that:
- Maximum flow rate Q1, which is achieved on the extension stroke of the load cylinder (retraction of the test cylinder) is ***12.5 l/min***;
- Maximum flow rate Q2, which is achieved on the extension stroke of the load cylinder (retraction of the test cylinder) is ***20 l/min***.

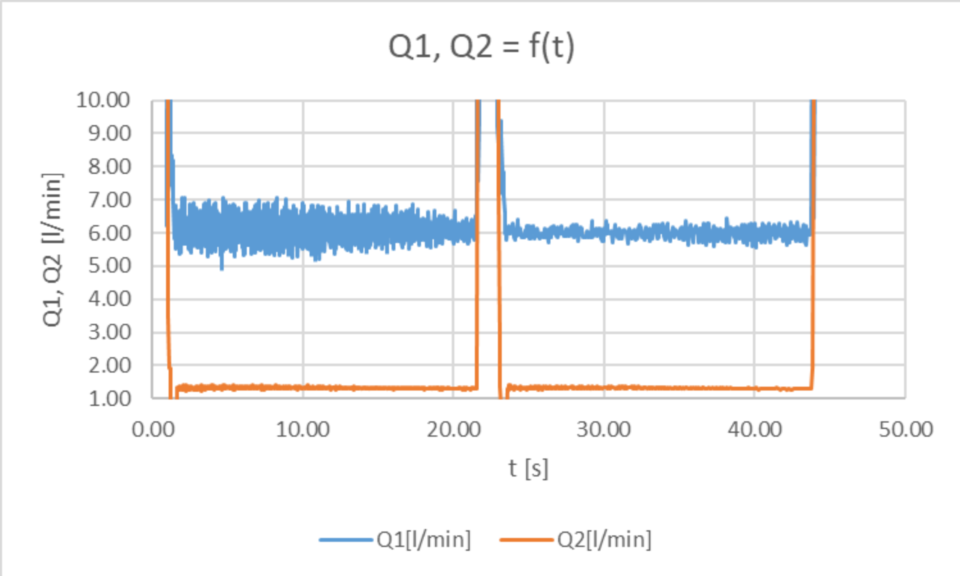

Fig. 10. Detail: time-variation of flow rate Q1

Figure 10 shows a detail of the flow rate Q1 variation [5], made for two full strokes of the load cylinder (extension + compression), over the ***1-10 l/min*** flow rate range; this range does not contain the flow rate Q2 variation, too.
One can notice that the flow rate Q1 variation, of ***maximum ± 1 l/min***, relative to the average value of ***6 l/min***, on the first compression stroke of the load cylinder, drops to a ***maximum of ± 0.5 l/min***, relative to the same average value, on the second compression stroke of the load cylinder. The explanation lies in the incomplete venting of the hydraulic circuits of the cylinders before the experimental tests began.

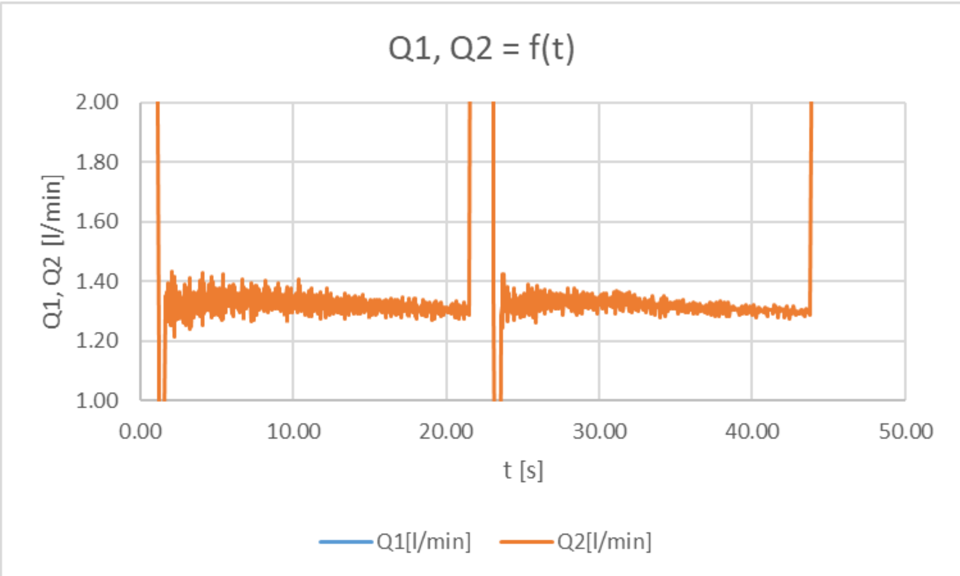

Fig. 11. Detail: time-variation of flow rate Q2

Time-variation of flow rate Q2 [5], over two compression strokes of the load cylinder, over the ***1-2 l/min*** flow rate range, is shown in detail in figure 11. One can notice that the flow rate Q2 variation is max. **± *0.1 l/min*** relative to the average value of ***1.3 l/min***.

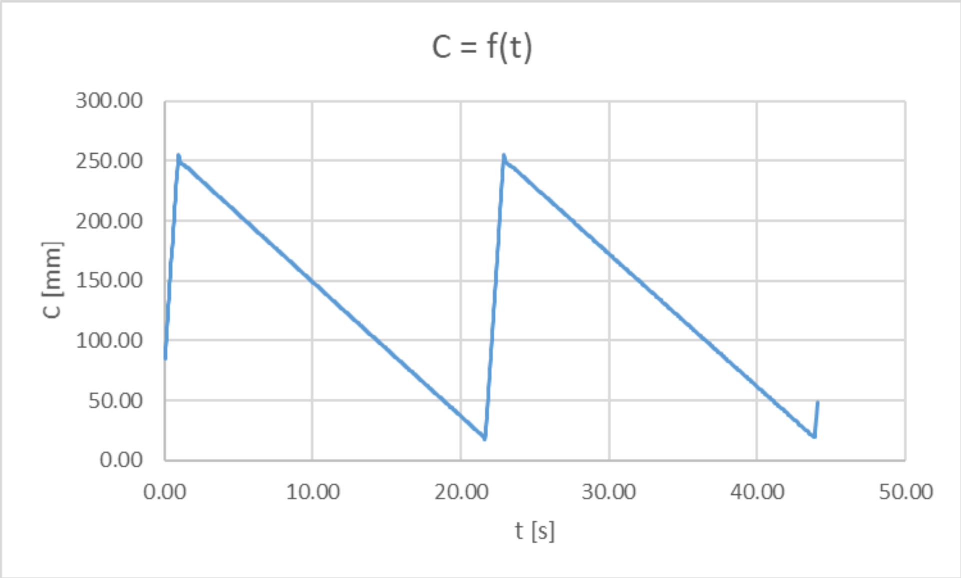

Fig. 12. Time-variation of cylinder stroke

Figure 12 shows the time-variation of the stroke of the two (test and load) hydraulic cylinders on the bench, when the load cylinder makes two full strokes (extension + compression). One can notice that the time to complete the compression stroke (test cylinder advance under constant load) is much longer than the time to complete the extension stroke (test cylinder idle retraction).
The advance speed of the test cylinder under load is about ***16 times lower*** than its idle retract speed because on the idle retraction stroke the test cylinder is fed with the full flow rate of the pump within the pumping unit, while on the advance under load stroke the same cylinder is fed only with the flow rate from the minibooster high-pressure connection.

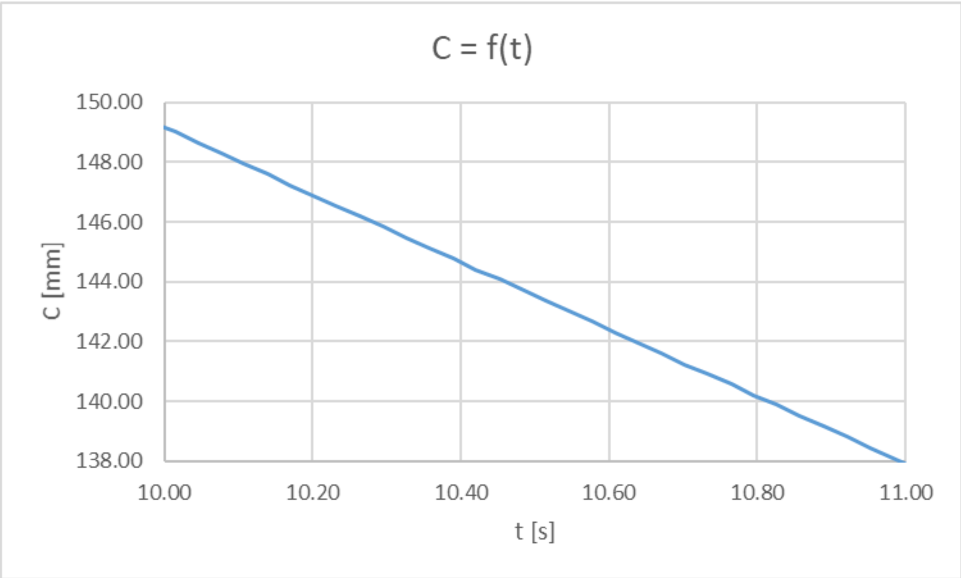

Fig. 13. Detail: time-variation of cylinder stroke

On the detail in figure 13, made for a time duration of ***1 second*** (in the range of ***10-11 s***) and a ***12-millimeter*** load cylinder compression stroke segment (in the range ***138-150mm***) one can notice that the displacement of hydraulic cylinders on the test bench is roughly linear [5].

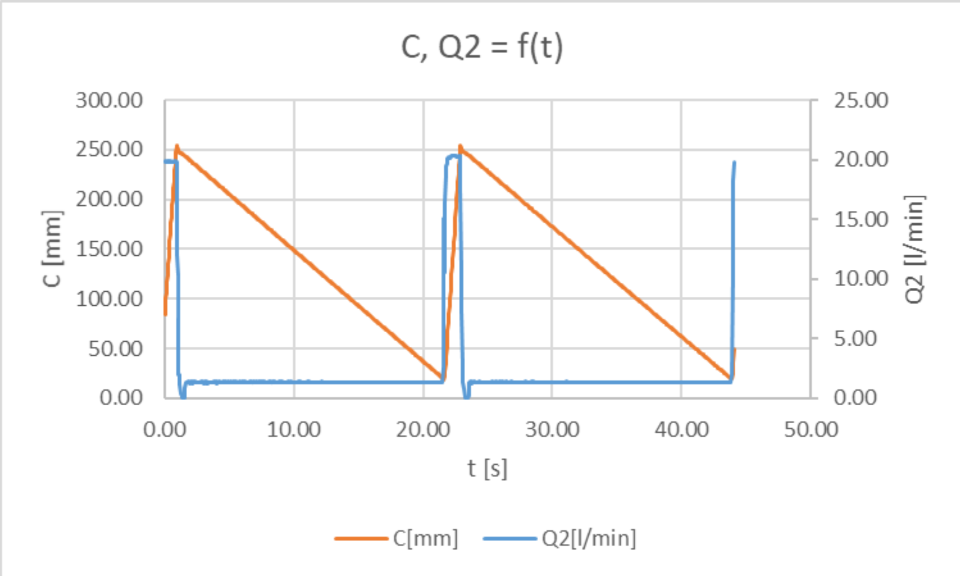

Fig. 14. Time-variation of load cylinder stroke and flow rate

Figure 14 shows the time-variation of the load cylinder stroke and flow rate over two full strokes (extension + compression). One can notice that:

- During load cylinder extension (approx. ***1.31 s***) the maximum flow rate is approx. ***20 l/min***;
- During load cylinder compression (approx. ***15.6 s***) the maximum flow rate is approx. ***1.3 l/min***;
- Small variations in the load cylinder flow rate cause small deviations from its linear displacement.

3.2 Comparative analysis between the variations of displacement of hydraulic cylinders on the test bench

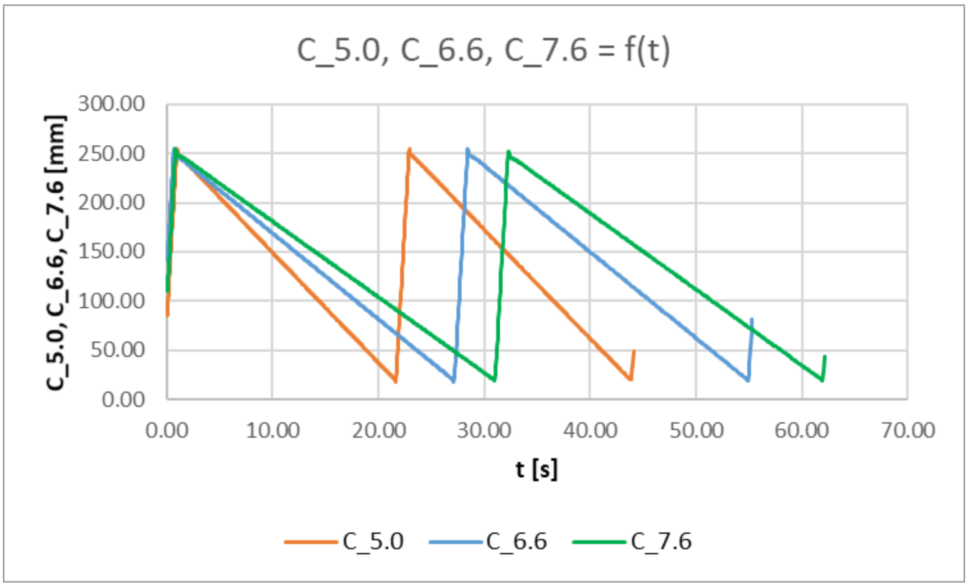

Fig. 15. Comparative analysis between the variations of displacement of hydraulic cylinders

After completing the ***1st set*** of tests for the pumping unit equipped with the minibooster ***i=5.0***, the following steps have been taken:
- The minibooster ***i=5.0*** has been replaced with a minibooster ***i=6.6*** and the ***2nd set*** of tests has been carried out under the same conditions;
- The minibooster ***i=6.6*** has been replaced with a minibooster ***i=7.6*** and the ***3rd set*** of tests has been carried out under the same conditions;
- The results from the three sets of measurements have been superimposed on the same graph of time-variation of the displacement of hydraulic cylinders, figure 15.

Figure 15 shows a comparison between the displacements of the load cylinder on the bench, equipped with displacement transducer, under the following conditions:
- The pumping unit, which supplies the test cylinder of the bench, is successively equipped with the three miniboosters, with different amplification factors (i=5.0; i=6.6; i=7.6);
- The (test and load) cylinders on the bench make two full strokes of ***250 mm*** each, for each direction of displacement;
- The load cylinder creates approximately equal and constant resistive forces for the test cylinder, on its advance stroke, and zero load on its retraction stroke.

4. Conclusions

- ***Displacement of the cylinders on the bench is approximately linear*** for the three cases of equipping the pumping unit with miniboosters;
- ***Advance speed rate under load*** of the test cylinder (displacement slope) decreases with increasing the minibooster amplification factor;
- ***Idle*** (no load) ***retraction speed rate*** does not depend on the amplification factor of the minibooster;
- ***The test cylinder moves slowly***, but with no restraint or stiffness, ***on the advance stroke***, and ***fast***, ***on the retraction stroke***;
- ***Resistive force*** that the test cylinder can overcome is ***directly proportional to the amplification factor of the minibooster***.
- The tested pumping unit can be equipped with any of the three miniboosters;
- For applications with hydraulic cylinders that need to move smaller loads at higher speed rates, the unit will be equipped with a minibooster with i=5.0, while for higher loads and lower displacement speed rates, the unit will be equipped with miniboosters with i= 6.6 or i=7.6.

Acknowledgments

The research presented in this paper has been developed under Financial Agreement no. 272/24.06.2020, signed by the Ministry of European Funds / Ministry of Education and Research and S.C. HESPER S.A. Bucharest for the Innovative Technological Project titled “Digital mechatronic systems for generating pressure of 1000 bar, using hydraulic pressure intensifiers” (SMGP), project under implementation from 01.07.2020 to 30.06.2023. Financial support has also been granted under a project funded by the Ministry of Research, Innovation and Digitalization through Programme 1- Development of the national research & development system, Sub-programme 1.2 - Institutional performance - Projects financing the R&D&I excellence, Financial Agreement no. 18PFE/30.12.2021.

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