Experimental Research on Efficient Pumping at High Pressure Rates

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Abstract: *High-pressure pumping units consisting of low-pressure pumping units and oscillating minibooster-type pressure intensifiers are an efficient solution for generating high pressure rates in hydraulic drive systems. Such pumping units are typically used in static applications (burst tests for pipelines and tanks) and mobile applications with high loads on small strokes of hydraulic cylinders (hydraulic tools and presses). Through experimental research, carried out on a test stand that can load a high-pressure hydraulic cylinder with heavy, high-magnitude loads, the authors demonstrated the possibility of expanding the range of technical applications of these pumping units to mobile applications with high loads over the entire stroke of hydraulic cylinders. A low-pressure pumping unit - 4 kW, 1500 rpm, 0...200 bar - was used; it was successively equipped with three types of miniboosters with different gain factors (i) (i=5.0; i=6.6; and i=7.6, respectively).*

Keywords: *Low-pressure pumping units, minibooster, high-pressure pumping units, high-magnitude load hydraulic cylinders*

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 load of 700 bar.

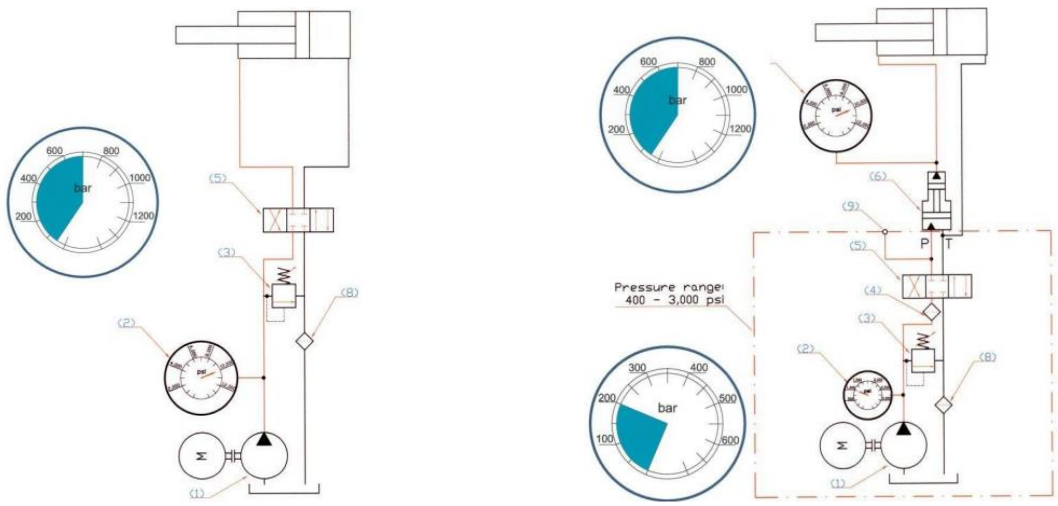

Fig. 1. Generating a pressure of 700 bar for actuating a hydraulic cylinder: left - with high-pressure pump; right - with low-pressure pump and hydraulic intensifier

In the hydraulic drive diagram [1] shown in Fig. 1-left, motor **M** drives **high-pressure pump (1)**, to direct hydraulic oil, at a pressure of 700 bar, indicated on pressure gauge (**2**), limited by 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 load of 700 bar.

One can move the same hydraulic cylinder to the right, with a load of 700 bar, according to the hydraulic drive diagram [1] shown in Fig. 1-right, where **low-pressure pump (1)**, pressure relief 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** of the hydraulic cylinders **under load,** or with the purpose of **achieving and maintaining the load at stroke end**.

2. Low-pressure pumping unit / system equipped with a minibooster; static applications

2.1 Building a low-pressure pumping unit / system equipped with miniboosters

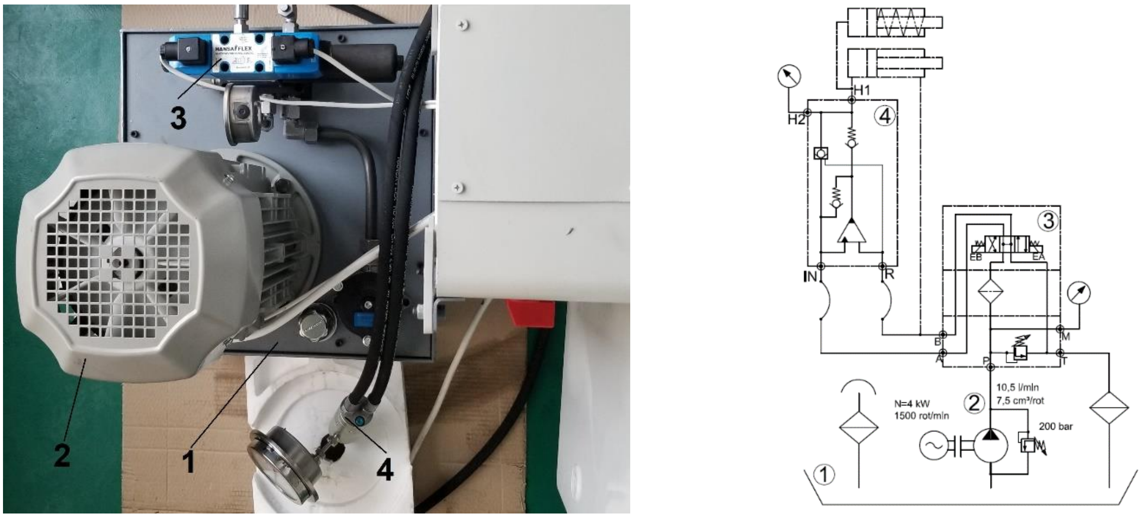

Fig. 2. Low-pressure pumping unit equipped with a minibooster: left side - physical model; right side - hydraulic schematic diagram

The authors developed the pumping unit shown in figure 2, where the notations have the following meanings: **1** – hydraulic oil tank, with return filter and fill/vent filter; **2** – low pressure electric pump, 4 kW, 1500 rpm, 200 bar, 10.5 l/min; **3** – block with hydraulic devices and pressure gauge (pressure valve, pressure filter, 4/3 hydraulic open center directional control valve, low pressure gauge); **P**, **T**, **M**, **A, B** - hydraulic block connections (pressure, tank, low pressure gauge, hydraulic test cylinder connections); **4** - minibooster (i=5, i=6.6, i= 7.6); **IN** - low pressure inlet connection (primary); **H1** - high pressure outlet connection (secondary); **H2** - high pressure gauge outlet connection (secondary); **R** - return connection.

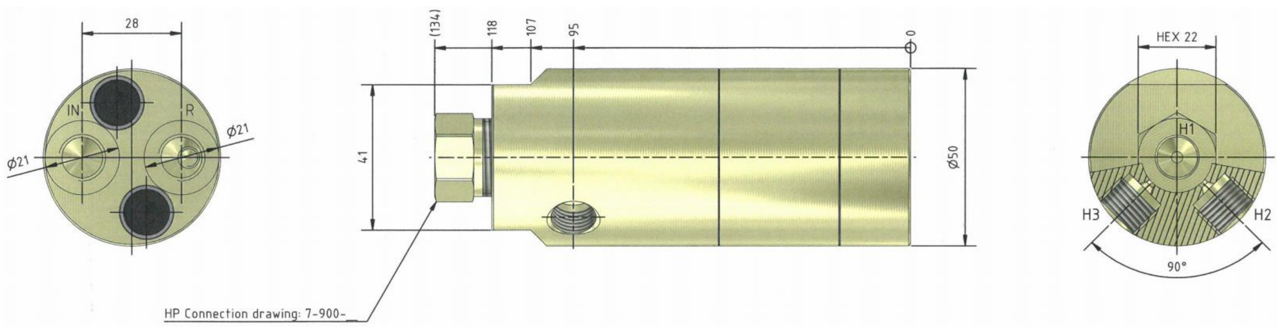

Fig. 3. Dimensions of the HC7 minibooster

The pumping unit in fig. 2 was successively equipped with three types of the HC7 minibooster [2], figure 3, which have the technical characteristics from table 1.

The maximum flow rate from the primary of the miniboosters, provided by the low-pressure pumping unit, is 10.5 l/min; this, being lower than the maximum allowed flow rate (from the manufacturer catalog) of the three miniboosters, allows the pumping unit to be equipped with any of the three minibooster variants.

Table 1: Technical characteristics of the HC7 minibooster

Gain factor i [-]	Pressure in primary / Pressure in secondary [bar]	Maximum primary flow rate [l/min]		Maximum secondary flow rate [l/min]		Primary connection dimensions		Secondary connection dimensions	
		Catalogue	**Used**	**Catalog**	**Used**	**IN**	**R**	**H1**	**H2**
5.0	0...200 / 0...1000	14.0	10.5	1.6	1.2	¼” BSP	¼” BSP	M22x 1.5	9/16-18UNF
6.6	0...200 / 0...1320	13.0	10.5	1.3	1.05	¼” BSP	¼” BSP	M22x 1.5	9/16-18UNF
7.6	0...200 / 0...1520	13.0	10.5	1.1	0.88	¼” BSP	¼” BSP	M22x 1.5	9/16-18UNF

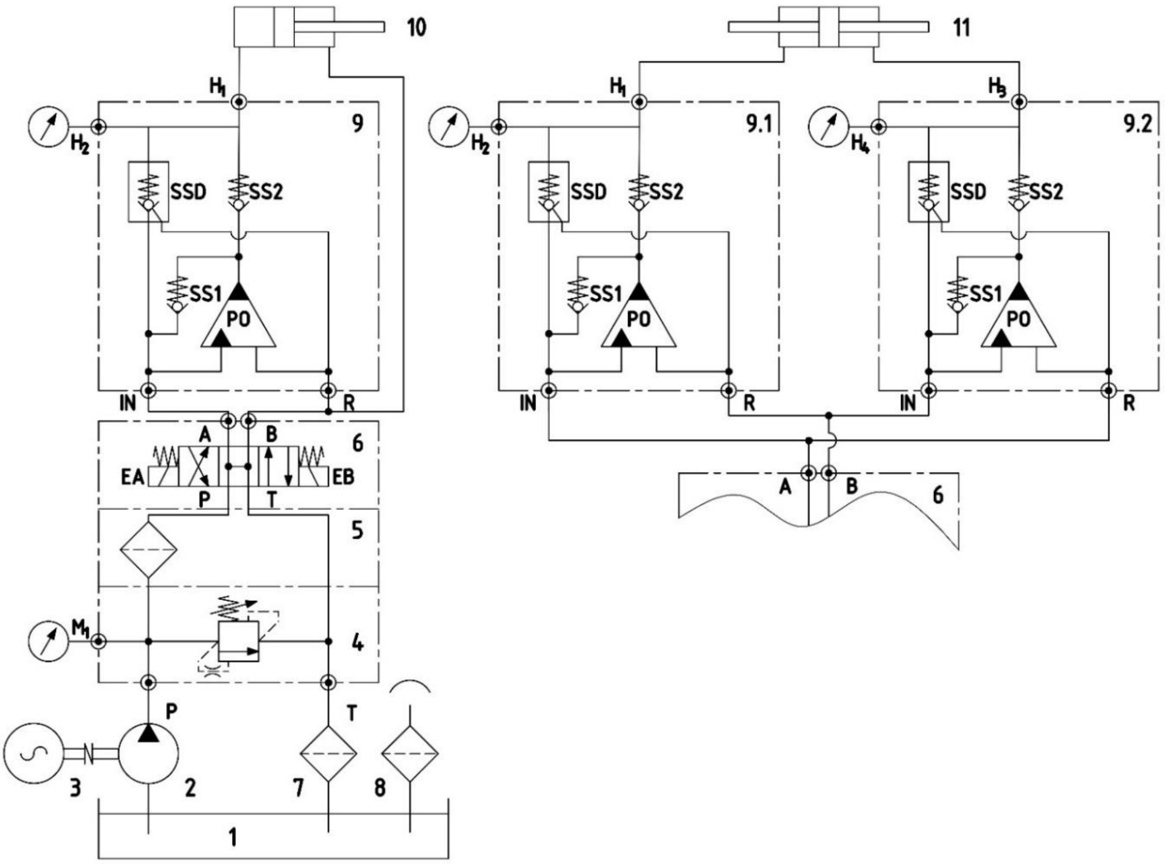

Fig. 4. High-pressure pumping system equipped with one or two miniboosters - hydraulic schematic diagram

The pumping **unit** in fig. 2 can be converted into the high-pressure pumping **system** [3] equipped with miniboosters shown in figure 4. It consists of an oil tank (**1**), from which a fixed flow rate low-pressure pump (**2**) sucks; the latter is driven by a constant speed electric motor (**3**) and discharges into the connection (**P**) of a normally closed modular pressure control valve (**4**), the pump discharge circuit passing through a modular pressure filter (**5**) and through the connection (**P**) of an 4/3 electrohydraulic open center modular directional control valve (**6**), and the connection (**T**) of the directional control valve being connected to the tank, through a hydraulic circuit that passes through the body of the modular pressure filter, the body of the modular pressure control valve, the connection (**T**) of this valve, and the return filter (**7**), located on the oil tank cover, in the vicinity of a fill and vent filter (**8**).

The system is characterized by the fact that the connections (**A**) and (**B**) of the electrohydraulic directional control valve can be connected to either the inlet and return connections (**IN**, **R**) of a minibooster (**9**), with the high-pressure connection (**H1**) coupled to the piston chamber connection of a hydraulic cylinder (**10**), which operates under heavy load only on the advance stroke, which has the rod chamber port connected to the directional control valve port (B), or to the inlet and return connections (**IN**, **R**) of two miniboosters (**9.1**) and (**9.2**), connected in series in the sequence (**$IN_{9.1}$-$R_{9.2}$**) and (**$R_{9.1}$-$IN_{9.2}$**), the high-pressure connections of these miniboosters being coupled to the connections of the volumetric chambers of the hydraulic cylinder (**11**), which operates under heavy load in both directions of displacement.

2.2 Testing a low-pressure pumping unit equipped with miniboosters; static applications

Testing of the low-pressure pumping unit, successively equipped with the miniboosters listed in table 1, was carried out, by plugging the **H1** high-pressure connection of the minibooster (fig. 2-right) and adjusting the pressure on the **IN** inlet connection of the minibooster (fig. 2-right), in the range 0...200 bar.
The proportionality between the pressures on the **IN** and **H1** connections (fig. 2-right) of the minibooster was noticed, the proportionality factor being approximately equal to the gain factor (**i**) of the minibooster.
The maximum pressure rates generated by the pumping unit, which can be read on the high pressure gauge mounted in the **H2** connection of the minibooster, are shown in figure 5.

i=5.0
p_{IN}=200 bar; p_{H2}=960 bar

i=6.6
p_{IN}=200 bar; p_{H2}=1290 bar

i=7.6
p_{IN}=200 bar; p_{H2}=1540 bar

Fig. 5. Tests on static applications of low-pressure pumping unit equipped successively with three types of miniboosters

3. Test stand for low-pressure pumping units equipped with a minibooster; dynamic applications

Among the applications of pumping units / systems equipped with miniboosters, **specific to fixed hydraulics** [4], there are: high-load bolt hydraulic pretensioners, figure 6-a; tunnel boring machines; installations on offshore oil platforms; railway maintenance equipment; life-saving equipment (extrication of car accident or earthquake victims); rock and stone splitters; hydraulic torque wrenches; hydraulic clamping systems of machine tools.
Among the applications of pumping units / systems equipped with miniboosters, **specific to mobile hydraulics** [5], comprising small cylinders with high forces, there are: heavy duty mobile stone crushers, figure 6-b; hook-lift trailers, figure 6-c; excavators and mini excavators, figure 6-d; hydraulic concrete crushing and breaking equipment used in demolitions, figure 6-e; mobile hydraulic jacks, figure 6-f; hydraulic tools mounted in aerial lifts. In most of these applications the hydraulic cylinders have heavy and variable dynamic loads.

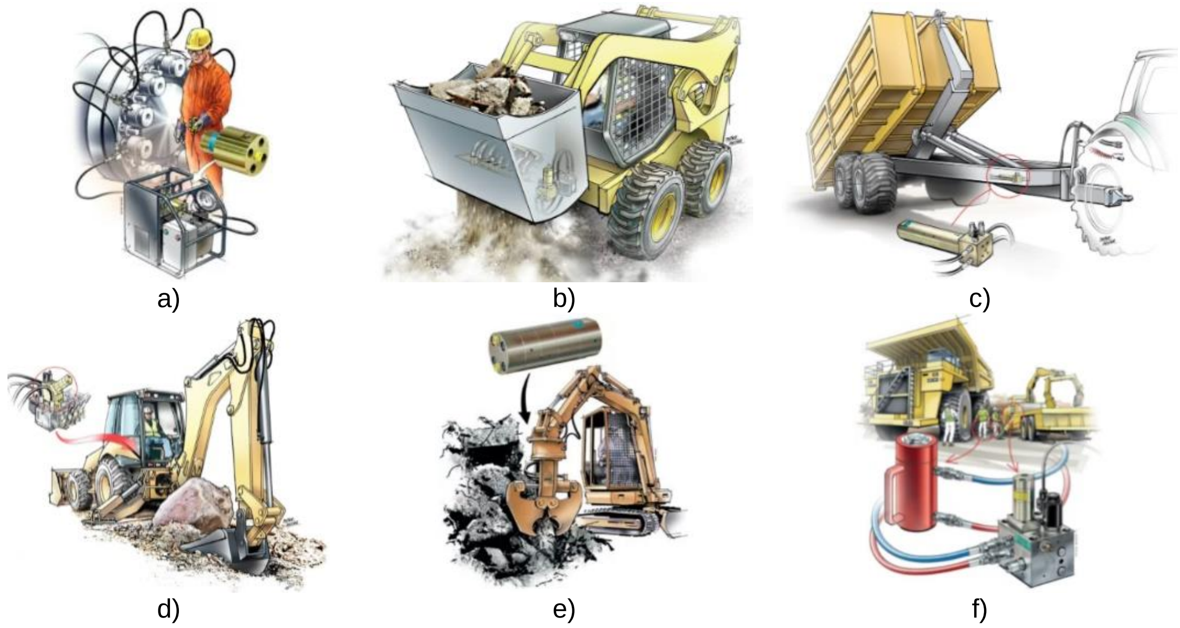

Fig. 6. Applications of pumping units / systems equipped with miniboosters

3.1 Building a stand for testing pumping units / systems equipped with miniboosters

The stand [6] in figure 7 consists of a support (**1**) for fixing two hydraulic cylinders, closed metal frame type, on which the body of a test cylinder (**2**) and the body of a load cylinder (**3**) are attached, with the rods fixed in the coupling (**C**), the *active chamber of the test cylinder* being supplied, alternatively left and right depending on the direction of displacement of the cylinder, from a tank (**4**), through the high-pressure connection (**H1**) of a minibooster (**13**), with a high-pressure pumping system comprising a low-pressure pump (**6**), driven by the electric motor (**7**), whose discharge pressure is controlled by a normally closed valve (**8**) and whose oil flow is filtered with a pressure filter (**9**); the active chamber of the test cylinder distributes oil flow by means of an 4/3 electrohydraulic open center directional control valve (**10**) which has consumers (**A**, **B**) coupled to the inlet and return connections (**IN**, **R**) of the minibooster, respectively, the consumer (**B**) being connected, alternately left and right depending on the direction of displacement of the cylinder, to the *passive chamber of the test cylinder*; the high-pressure pumping system is also provided with a return filter (**11**), and a fill and vent filter (**12**), both located on the tank cover, and the stand is also equipped with an electrical panel (**19**) for control and data acquisition, which sends the electric control signals (**EA**, **EB**) to the electrohydraulic directional control valve, (**a**)- to the pump drive electric motor, (**b**)- to the load control proportional pressure valve, and acquires the data (**c**,**d**,**e**,**f**) from the (**P1**, **P2**) pressure and (**Q1**, **Q2**) flow transducers, respectively, located on the filling / discharging circuits of the load cylinder chambers, as well as the data (**g**), from the stroke transducer embedded in the load cylinder.

This stand is characterized by the fact that, although intended for high-pressure tests for dynamic applications, hydraulic devices for pressure control, oil filtration and oil flow distribution that equip the stand are low pressure, and pressure and flow sensors are cheaper, because they are of lower pressure than the test pressure, because they are mounted on the hydraulic circuits of the load cylinder, which has larger active working surfaces in the piston chamber and rod chamber than those of the test cylinder, filling the *active chamber of the load cylinder* being done by free fall from a tank (**5**) located at height, alternatively left and right depending on the direction of displacement of the cylinder, through a check valve (**14**), or another check valve (**16**), respectively, and the *passive chamber of the test cylinder* being discharged to the same tank, alternatively left and right depending on the direction of displacement of the cylinder, through a check valve (**15**) and a proportional pressure valve (**18**) for load control, or another check valve (**17**) and the same proportional pressure valve (**18**), respectively.

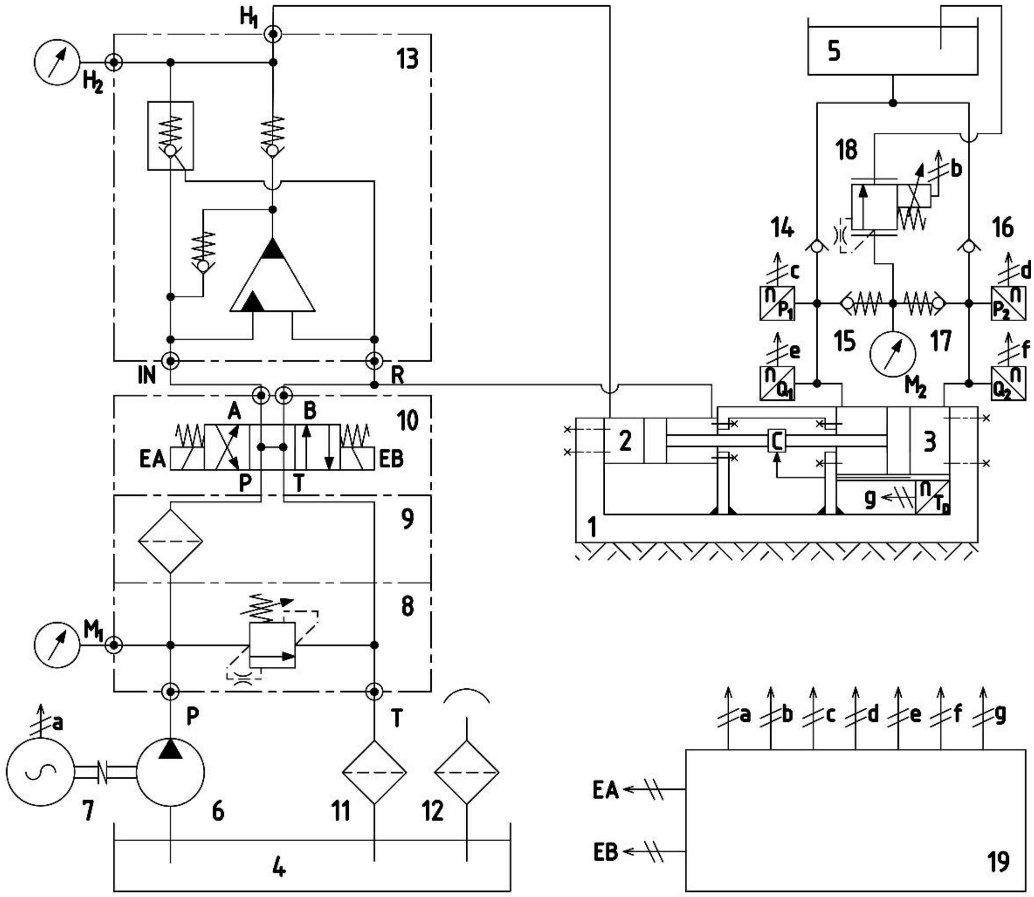

Fig. 7. Stand for testing high-pressure pumping systems equipped with a minibooster - *hydraulic schematic diagram*

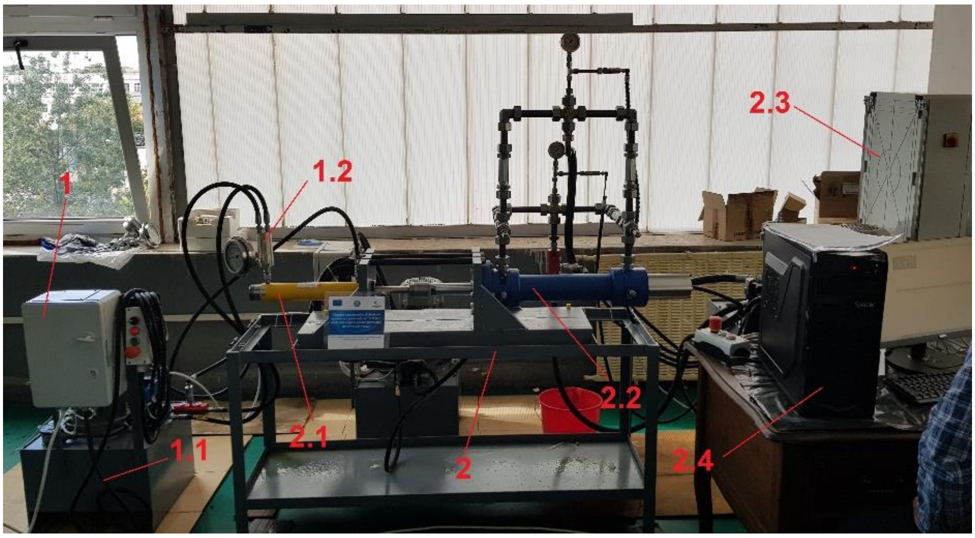

Fig. 8. Stand for testing high-pressure pumping systems equipped with a minibooster - *physical model*: **1**- high-pressure pumping unit (HPPU); **1.1**- low-pressure pumping unit; **1.2**- minibooster; **2**- stand for testing the HPPU; **2.1**- test cylinder (TC); **2.2**- load cylinder (LC); **2.3**- pumping unit for feeding the LC; **2.4**- control and experimental data acquisition system

Compared to the principle hydraulic diagram in fig.7, in the physical model of the stand in fig.8 the feeding of the load cylinder is done with a pumping unit - item **2.3** (fig.8), not by free fall, from the tank at height - item **5** (fig.7).

3.2 Testing a low-pressure pumping unit equipped with miniboosters; dynamic applications

Figure 9 shows a comparison between the displacements of the test cylinder on the stand, coupled with the load cylinder equipped with a displacement transducer, under the following conditions:
- the low-pressure pumping unit, which feeds the test cylinder of the stand, is successively equipped with 3 miniboosters, with different gain factors (i=5.0; i=6.6; i=7.6);
- for the minibooster with gain factor **i=5.0:** number of data records acquired = **1050**; duration of recordings = **44.075 s**;
- for the minibooster with gain factor **i=6.6:** number of data records acquired = **1190**; duration of recordings = **55.309 s**;
- for the minibooster with gain factor **i=7.6:** number of data records acquired = **1281**; duration of recordings = **62.120 s**;
- the (test and load) cylinders on the stand make two complete strokes of ***250 mm*** for each direction of travel;
- the load cylinder creates approximately equal and constant **resistive forces** for the test cylinder (corresponding to a pressure adjusted with the proportional valve of **800 bar**) on the **advance stroke** of the latter, and **zero load** on the **retreat stroke** of the latter.

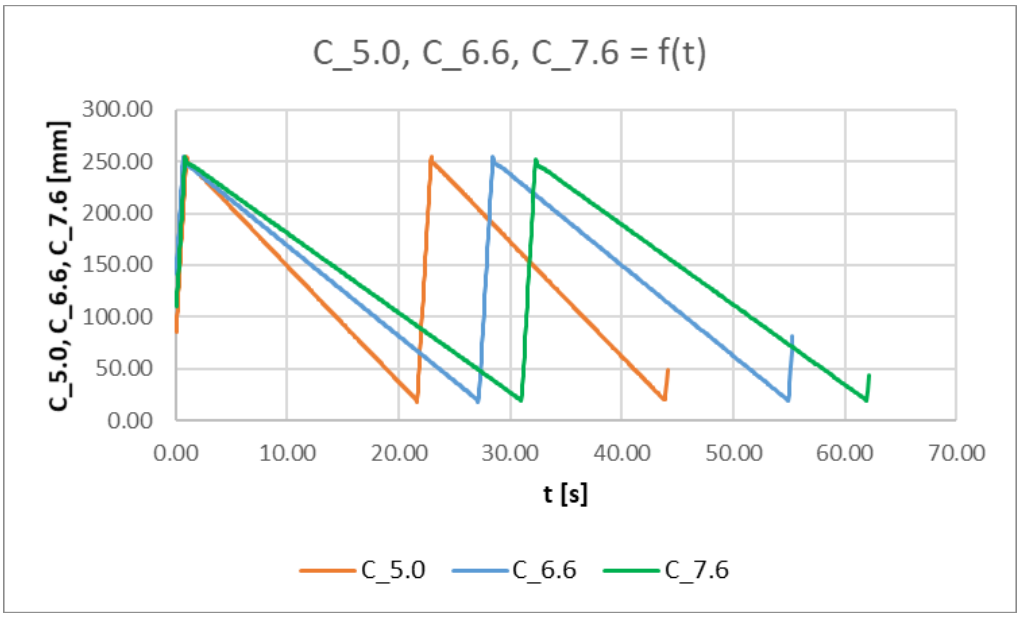

Fig. 9. Comparison between the displacements of the test cylinder, connected to the pumping unit successively equipped with three miniboosters (i=5.0, i=6.6, i=7.6)

Superimposing the results of the three tests on the graph in figure 9, **it is found that**:
- **displacement of the cylinders** on the stand is approximately linear, for the three cases of equipping the pumping unit with a minibooster;
- **forward speed rate under load** of the test cylinder (displacement slope) decreases with the increase in the gain factor of the minibooster;
- **idle** (no load) **backward speed rate** does not depend on the gain factor of the minibooster;
- **the test cylinder moves slowly**, but no restraints or stiffening, **on the advance stroke** and **fast**, **on the retract stroke**;
- **the resistive force** that the test cylinder can overcome is directly proportional to the gain factor of the minibooster.

4. Conclusions

- for **mobile applications** with **high-magnitude loads over the entire cylinder stroke**, the low-pressure pumping unit can be **equipped with any of the three miniboosters**;

- if used in applications with hydraulic cylinders that need to overcome **smaller loads**, which it has to move **faster**, the unit will be equipped with a minibooster with **i=5.0**, and for **higher loads** and **lower** displacement **speed rates**, the unit will be equipped with miniboosters with **i= 6.6** or **i=7.6;**
- if the pumping unit is used for displacement under load only on the advance stroke of a hydraulic cylinder, then the unit is equipped with a single minibooster, while if used for two-way displacement under load, the pumping unit will turn into a pumping system, which will be equipped with two miniboosters connected according to the hydraulic schematic diagram in figure 4.

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