Experimental Demonstrations of Extension of Technical Applications for Pumping Units Equipped with Miniboosters

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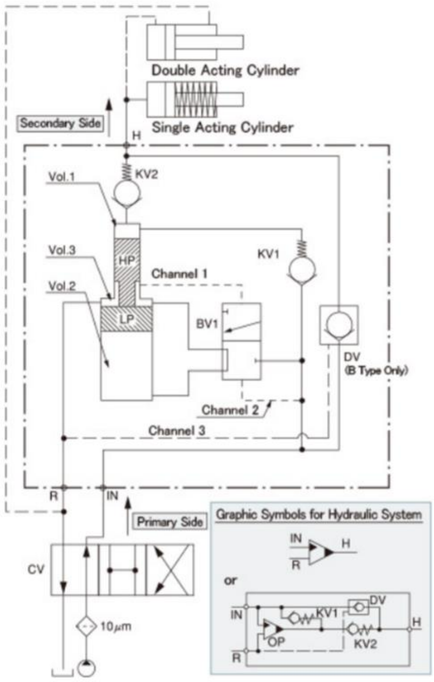
Abstract: *The authors of this article have developed three high-pressure pumping modules, composed of low-pressure electric pumps, equipped with oscillating hydraulic pressure intensifiers (miniboosters), which they intended to use to supply hydraulic cylinders of small dimensions and high forces. Due to the flow and pressure pulsations that occur at the outlet of the minibooster secondary side, such pumping modules are recommended for applications with static loads, which imply generating and maintaining high pressures in the volumes of closed spaces (pipes, tanks), or at the end of the stroke of hydraulic cylinders (presses). The authors have demonstrated, on an experimental test bench, which includes a 700 bar hydraulic test cylinder and a load simulation hydraulic cylinder, that the three pumping modules can also be used for the relatively uniform displacement of the dynamic load test cylinder over its entire stroke.*

Keywords: *High-pressure pumping module, minibooster, dynamic load, hydraulic cylinder, uniform displacement*

1. Introduction

A **high-pressure pumping module** may be equivalent to a **low-pressure pumping group** (oil tank + fixed flow electric pump + pressure valve + hydraulic directional control valve + pressure filter) **equipped with an oscillating hydraulic pressure intensifier** (minibooster).
The classic application for the use of these pumping modules, whose hydraulic operating diagram is shown in Figure 1, is the supply of single or double acting hydraulic cylinders, which move with no load over the entire advance stroke, except at the end of the stroke, where they have to achieve and maintain high clamping / pressing forces. Basically, the high-pressure pumping module **operates at low pressure during the displacement of hydraulic cylinder**, with maximum flow, which produces high speed of displacement of the cylinder; **high-pressure operation only takes place at the stroke end** of the cylinder, where the displacement is zero, and the high-pressure flow is only necessary to cover any internal losses on the high-pressure circuit.
When the slide valve of the pumping module hydraulic directional control valve switches to the left position of the hydraulic symbol (Fig. 1), fixed pump flow reaches the piston chamber of the (single or double acting) hydraulic cylinder directly, bypassing low / high-pressure pistons (**LP**, **HP**) and bistable distribution valve (**BV1**), the two check valves (**KV1**, **KV2**) and unlockable check valve (**DV**) being open, and the cylinder starts its **advance stroke** at full speed.
When the cylinder piston reaches the end of the advance stroke, or on the onset of the load, the three check valves (**KV1**, **KV2**, **DV**) get closed, and the minibooster starts up and pumps oil at high pressure, namely:
- The two pistons (**LP**+**HP**) move in both directions;
- Through the hydraulically operated distribution valve the oil discharged by the fixed pump fills **volume 2** (when pistons **LP**+**HP** move upwards) or **volume 2** is discharged through **volume 3** to the tank (when pistons **LP**+**HP** move downwards);
- The oil at low pressure is sucked into the volume V1 (**KV1** open, **KV2** closed), when pistons move downwards;
- The oil at high pressure is pumped out of the volume V1 (**KV1** closed, **KV2** open), when pistons move upwards.

Up and down displacement of the pistons stops (the minibooster stops working) when the pressure on fitting **H** of the minibooster reaches the set value of the safety valve (not shown in fig.1) of the pump (the pump discharges through the safety valve to the tank). The pressure on fitting **IN** of the minibooster is amplified on fitting **H**, with a value equal to the amplification ratio **i**. If the pressure in fitting **H** decreases due to internal oil leaks, the minibooster starts working again to restore high pressure.
To start the **retraction stroke** of the cylinder, the slide valve of the pumping module hydraulic directional control valve switches to the right position of the hydraulic symbol; unlockable check valve **DV** receives the command to open from the pump, and the hydraulic cylinder piston chamber is discharged via **DV** to the tank.



Caption:
LP = low-pressure piston;
HP = high-pressure piston;
BV1 = bistable distribution valve, hydraulically controlled through pilot channels *1* and *2*, for changing the direction of displacement of the pistons;
DV = unlockable check valve, controlled through pilot channel *3*, for discharging high-pressure oil from the chamber of the consumer;
KV1, **KV2** = check valves for oil inlet / outlet in / from high-pressure chamber **Vol.1**;
Vol.2 = volume of oil discharged to the tank by distribution valve **BV1**, via volume **Vol.3**;
IN = inlet fitting to the primary side of the minibooster;
R = outlet (return) fitting from the primary side of the minibooster;
H = secondary side of the minibooster outlet fitting;
CV = hydraulic directional control valve for changing the direction of displacement of the hydraulic cylinder, single or double acting, supplied via high-pressure outlet fitting **H**, from the secondary side of the minibooster.

Fig. 1. Classic application for using pumping modules equipped with minibooster [1]

2. High-pressure pumping modules equipped with miniboosters

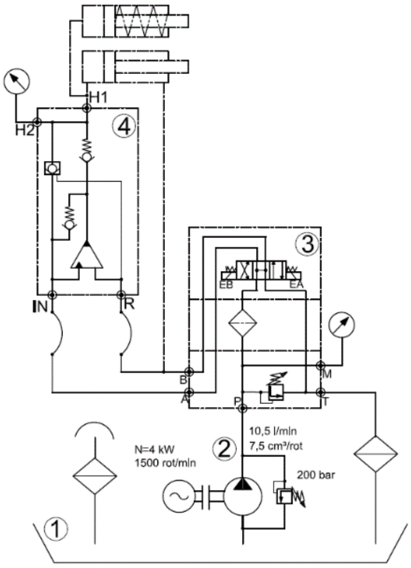
Figure 2 below shows the three high-pressure pumping modules developed by the authors (MP1, MP2, MP3), of different power, pressure amplification ratios and flow rates.

Fig. 2. The three high-pressure pumping modules equipped with miniboosters

Table 1: Technical characteristics of high-pressure pumping modules

Technical characteristics	Pumping module MP1	Pumping module MP2	Pumping module MP3
Overall dimensions [mm]	443 x 425 x 880	443 x 425 x 880	443 x 425 x 880
Geometric volume of the pump $V_g[cm^3/rev]$	8	6	4.20
Pump flow rate *Q[l/min]*	11.77	8.95	6.10
Oil tank volume *V[l]*	38	38	38
Pump drive electric motor power *N[kW]*	4	3	2.2
Pump drive electric motor speed *n[rev/min]*	1460	1455	1455
Rated pump pressure (IN minibooster) $p_{IN}[bar]$	adjustable 0...200	adjustable 0...200	adjustable 0...200
Pressure amplification ratio $i = p_{H1} / p_{IN}$ [-]	5	6.6	7.6
Amplified pressure p_{H1} [bar]	adjustable 0...1000	adjustable 0...1320	adjustable 0...1520
Flow rate at amplified pressure Q_{H1} [l/min]	11.77...0.75	8.95...0.40	6.10...0.30
High-pressure outlet fitting of minibooster *H1*	internal thread M22 x 1.5	internal thread M22 x 1.5	internal thread M22 x 1.5

The technical characteristics of these products are shown in Table 1, and their hydraulic operating diagram in Figure 3.



Caption:

1 = hydraulic tank with return filter and filling and venting filter;
2 = electric pump (*4 kW, 3 kW, 2.2 kW*);
3 = block with hydraulic devices (direct pressure control valve, modular pressure filter, 4/3 electrohydraulic directional control valve, low pressure gauge);
4 = minibooster (*i=5, i=6.6, i= 7.6*);
IN = low-pressure inlet fitting of the minibooster (primary side of the minibooster);
H1 = high-pressure outlet fitting of the minibooster (secondary side of the minibooster);
H2 = high pressure gauge fitting (secondary side of the minibooster);
R = return fitting (primary side of the minibooster).

Fig. 3. Hydraulic operating diagram of the three high-pressure pumping modules

3. Experimental tests on high-pressure pumping modules equipped with miniboosters

Static load tests and dynamic load tests on the high-pressure fitting of the minibooster have been carried out for each of the three pumping modules [2]...[7].

3.1 Static load tests on the pumping modules

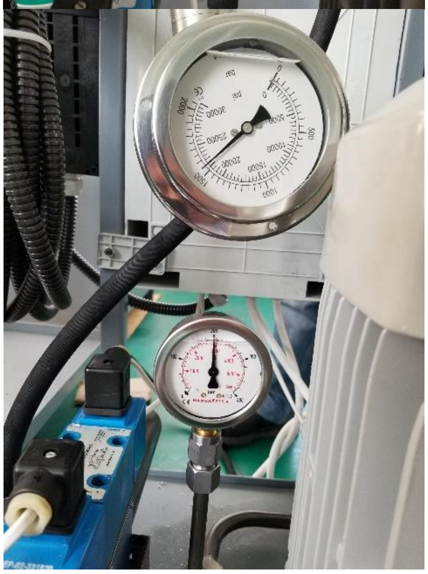
Static load tests on pumping modules MP1, MP2, and MP3 have been carried out with an M22x1.5 plug, mounted on fitting *H1* of the minibooster and adjusting the pressure in the primary side in the range 0 ... 200 bar. Figure 4 shows the maximum pressure values achieved by the three pumping modules (p_{Hmax}).

Pumping module MP1
Product code:
MPIP-HP1-8.0-HC7-5.0-0.0

On the large pressure gauge:
p_{H2} = 960 bar
On the small pressure gauge:
p_{IN} = 200 bar
Amplification ratio:
i = 960 / 200 = 4.80

Pumping module MP2
Product code:
MPIP-HP1-6.0-HC7-6.6-0.0

On the large pressure gauge:
p_{H2} = 1290 bar
On the small pressure gauge:
p_{IN} = 200 bar
Amplification ratio:
i = 1290 / 200 = 6.45



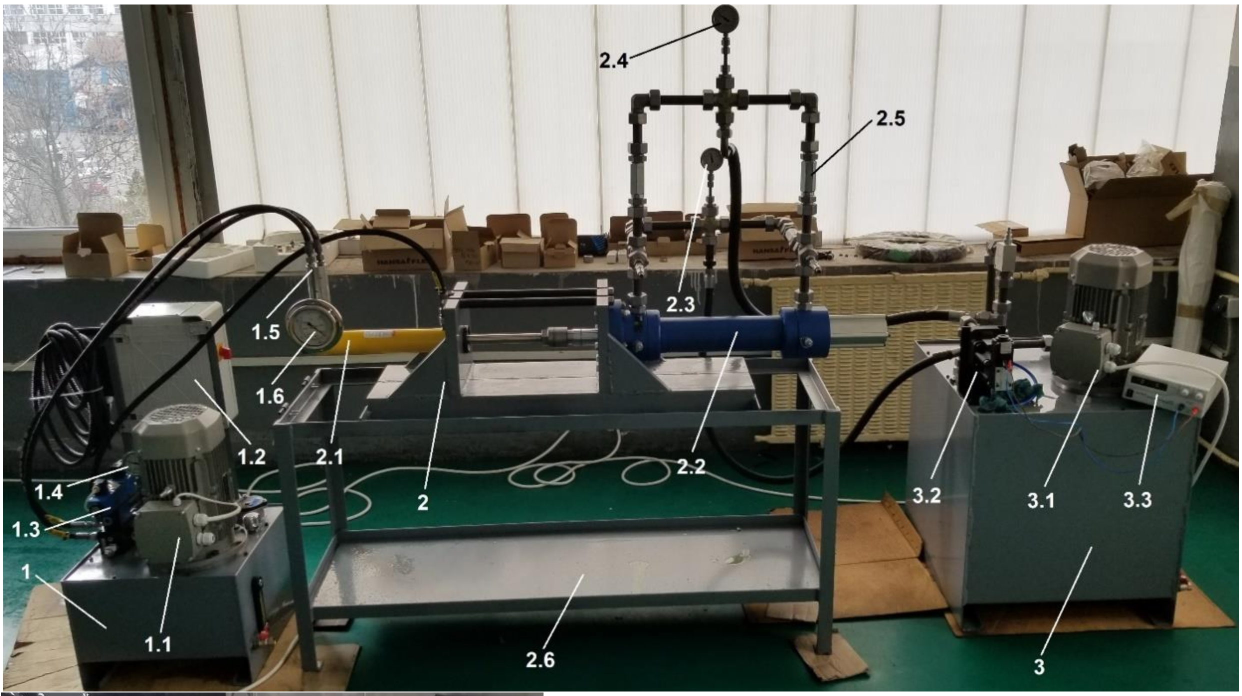
Pumping module MP3
Product code:
MPIP-HP1-4.3-HC7-7.6-0.0

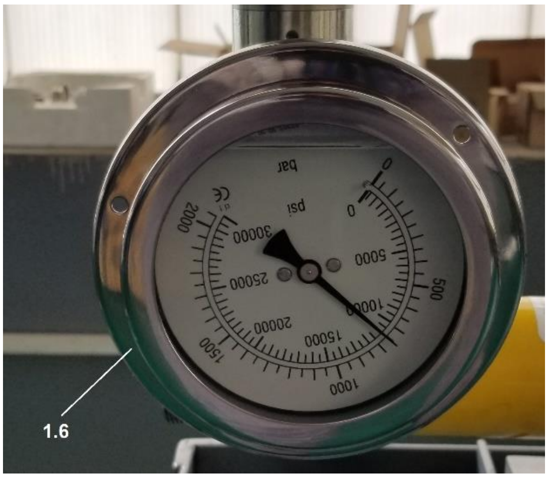
On the large pressure gauge:
p_{H2} = 1540 bar
On the small pressure gauge:
p_{IN} = 200 bar
Amplification ratio:
i = 1540 / 200 = 7.70

Fig. 4. Maximum pressure values achieved with the three pumping modules (MP1, MP2, MP3)

3.2 Dynamic load tests on the pumping modules

The dynamic load tests of the three pumping modules have been carried out on the test bench for high-pressure pumping modules and systems, product code SPMS-0.0, which is shown in fig. 5.





Caption:

1 = Pumping module under tests (MP1, MP2, **MP3**);
1.1 = Electric pump (4 kW, 3 kW, **2.2 kW**);
1.2 = Electric panel;
1.3 = Block with hydraulic devices (**direct pressure control valve**, modular pressure filter, 4/3 electrohydraulic directional control valve, low pressure gauge);
1.4 = Low pressure gauge (it reads **100 bar**);
1.5 = Minibooster (i=5, i=6.6, **i=7.6**);
1.6 = High pressure gauge (it reads **750 bar**);
2 = Hydraulic cylinder fastening module;
2.1 = Test cylinder Ø38.1/ Ø25.4 x 257 (p_{max}= 700 bar);
2.2 = Load cylinder Ø80/ Ø45 x 300;
2.3, 2.4 = Pressure gauges for measuring pressure in the load cylinder chambers;
2.5 = Check valves (4 pcs.);
2.6 = Support frame;
3 = Hydraulic station for filling the load cylinder;
3.1 = Electric pump 2.2 kW, 60 cm^3/rev;
3.2 = Normally closed proportional pressure valve;
3.3 = Power supply for proportional electromagnet of normally closed pressure valve.

Note:
The pictures have been taken during experimental tests on pumping module MP3.

Fig. 5. Test bench for high-pressure pumping modules and systems with dynamic load

3.2.1 Dynamic load tests on module MP1

Module MP1 was connected hydraulically to the 700 bar test cylinder (HC) of the bench, with fitting H1 of the minibooster fixed to the piston chamber fitting and fitting B of the 4/3 electrohydraulic directional control valve fixed to the rod fitting. Seven measurements were performed, as follows:
Measurement 1: Maximum flow rate of pumping module MP1, idle, with no load, was determined by using a graded beaker and stopwatch (11.77 l / min);
*For the next measurements, the safety valve (SV) of the module was set to **160 bar**, taking into account two aspects: maximum working pressure of the test cylinder of the bench (700 bar); the safety valve of the module must not open during the displacement of the load cylinder of the bench (for Qs = 0, it results $Qp_{ump} = Q_{IN} = Q_H + Q_R$).*
Measurement 2: Flow rate of pumping module MP1, idle, with no load, with zero supply current of the normally closed proportional valve that simulates the load, was determined by measuring the time of a complete advance stroke of the test cylinder (stroke = 257 mm);
Measurements 3-7: Flow rates of pumping module MP1, with load, were determined for the normally closed proportional valve supply currents of 0.5A, 0.7A, 0.9A, 1.1A, 1.3A, simulating the load, by measuring the time of a complete advance stroke of the test cylinder. The results of the measurements are shown in Table 2 and Figure 6.

Table 2: Results of experimental tests with dynamic load on module MP1

Item no.	Measured values			Calculated values						
	Pressures [bar] *(p)*		Time / stroke [s/ 257 mm] *(t)*	Speed of HC [mm/s] *(V=c/t)*	HC Piston area [mm²] *(A_p)*	Flow rates [l/min] *($Q=A_p x V$)*			Force of HC [kN] *($F=p/A_p$)*	Ampl. ratio i [-]
	Setting of SV (primary side)	Load of HC secondary side)				on H1	max.	on R		
1	0	0	-	-	-	11.770	11.77	0.000	0.00	5
2	160	30	2.670	96.254	1140	6.583	11.77	5.186	3.42	5
3	160	150	16.145	15.918	1140	1.088	11.77	10.681	17.1	5
4	160	255	16.860	15.243	1140	1.042	11.77	10.727	29.07	5
5	160	375	17.860	14.389	1140	0.984	11.77	10.785	42.75	5
6	160	510	19.260	13.343	1140	0.912	11.77	10.857	58.14	5
7	160	625	23.265	11.046	1140	0.755	11.77	11.014	71.25	5

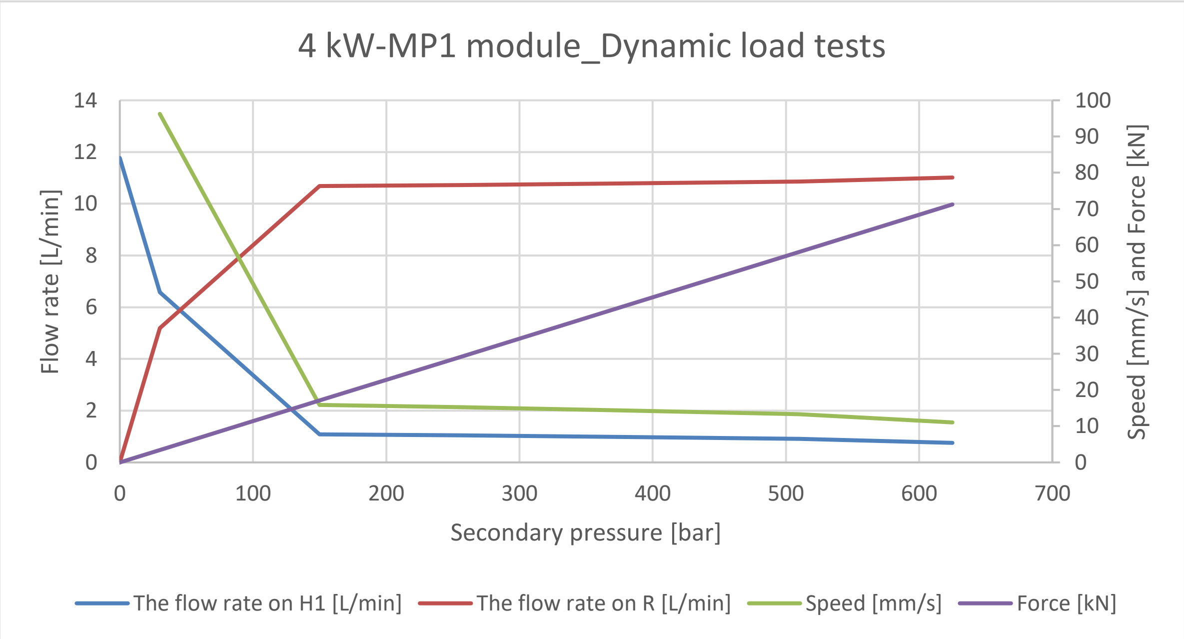


Fig. 6. Module M1: Variation of Q_{H1}, Q_R, speed, and force of test cylinder depending on p_{H1}

3.2.2 Dynamic load tests on module MP2

Module MP2 was connected hydraulically to the 700 bar test cylinder (HC) of the bench, with fitting H1 of the minibooster fixed to the piston chamber fitting and fitting B of the 4/3 electrohydraulic directional control valve fixed to the rod fitting. Seven measurements were performed, as follows:

Measurement 1: Maximum flow rate of pumping module MP2, idle, with no load, was determined using a graded beaker and stopwatch (8.955 l / min);

For the next measurements, the safety valve (SV) of the module was set to ***120 bar****, taking into account two aspects: maximum working pressure of the test cylinder of the bench (700 bar); the safety valve of the module must not open during the displacement of the load cylinder of the bench (for Qs = 0, it results* $Qp_{ump} = Q_{IN} = Q_H + Q_R$*).*

Measurement 2: Flow rate of pumping module MP2, idle, with no load, with zero supply current of the normally closed proportional valve that simulates the load, was determined by measuring the time of a complete advance stroke of the test cylinder (stroke = 257 mm);

Measurements 3-7: Flow rates of pumping module MP2, with load, were determined for the normally closed proportional valve supply currents of 0.4A, 0.7A, 0.9A, 1.1A, 1.3A, simulating the load, by measuring the time of a complete advance stroke of the test cylinder. The results of the measurements are shown in Table 3 and Figure 7.

Table 3: Results of experimental tests with dynamic load on module MP2

Item no.	Measured values			Calculated values						
	Pressures [bar] *(p)*		Time / stroke [s/ 257 mm] *(t)*	Speed of HC [mm/s] *(V=c/t)*	HC Piston area [mm²] *(A_p)*	Flow rates [l/min] *($Q=A_pxV$)*			Force of HC [kN] *($F=p/A_p$)*	Ampl. ratio i [-]
	Setting of SV (primary side)	Load of HC secondary side)				on H1	max.	on R		
1	0	0	-	-	-	8.955	8.955	0.000	0.00	6.6
2	120	30	3.373	76.193	1140	5.211	8.955	3.743	3.42	6.6
3	120	100	26.500	9.698	1140	0.663	8.955	8.291	11.40	6.6
4	120	200	30.770	8.352	1140	0.571	8.955	8.383	22.80	6.6
5	120	365	33.190	7.743	1140	0.529	8.955	8.425	41.61	6.6
6	120	500	36.280	7.083	1140	0.484	8.955	8.470	57.00	6.6
7	120	650	43.470	5.912	1140	0.404	8.955	8.550	74.10	6.6

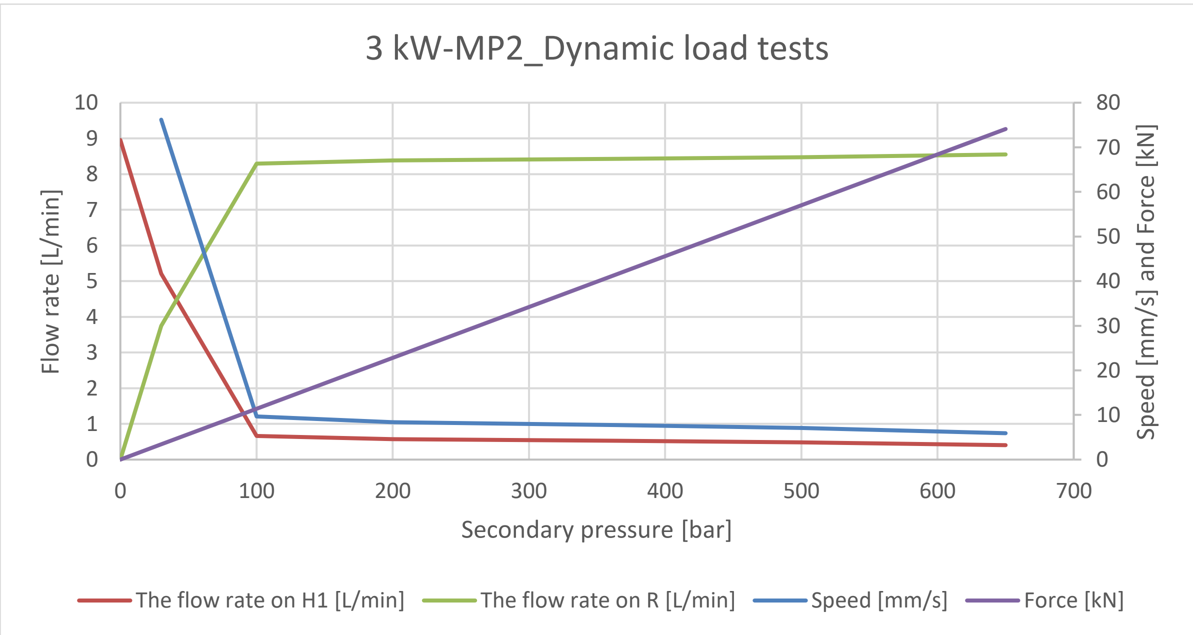


Fig. 7. Module M2: Variation of Q_{H1}, Q_R, speed, and force of test cylinder depending on p_{H1}

3.2.3 Dynamic load tests on module MP3

Module MP3 was connected hydraulically to the 700 bar test cylinder (HC) of the bench, with fitting H1 of the minibooster fixed to the piston chamber fitting and fitting B of the 4/3 electrohydraulic directional control valve fixed to the rod fitting. Seven measurements were performed, as follows:
Measurement 1: Maximum flow rate of pumping module MP3, idle, with no load, was determined using a graded beaker and stopwatch (6.10 l / min);
For the next measurements, the safety valve (SV) of the module was set to ***120 bar****, taking into account two aspects: maximum working pressure of the test cylinder of the bench (700 bar); the safety valve of the module must not open during the displacement of the load cylinder of the bench (for Qs = 0, it results* $Qp_{ump} = Q_{IN} = Q_H + Q_R$*).*
Measurement 2: Flow rate of pumping module MP3, idle, with no load, with zero supply current of the normally closed proportional valve that simulates the load, was determined by measuring the time of a complete advance stroke of the test cylinder (stroke = 257 mm);
Measurements 3-7: Flow rates of pumping module MP3, with load, were determined for the normally closed proportional valve supply currents of 0.5A, 0.8A, 1A, 1.2A, 1.3A, simulating the load, by measuring the time of a complete advance stroke of the test cylinder. The results of the measurements are shown in Table 4 and Figure 8.

Table 4: Results of experimental tests with dynamic load on module MP3

Item no.	Measured values			Calculated values						
	Pressures [bar] *(p)*		Time / stroke [s/ 257 mm] *(t)*	Speed of HC [mm/s] *(V=c/t)*	HC Piston area [mm²] *(A_p)*	Flow rates [l/min] *($Q=A_pxV$)*			Force of HC [kN] *($F=p/A_p$)*	Ampl. ratio i [-]
	Setting of SV (primary side)	Load of HC secondary side)				on H1	max.	on R		
1	0	0	-	-	-	6.100	6.10	0.000	0.00	7.6
2	100	30	5.176	49.652	1140	3.396	6.10	2.703	3.42	7.6
3	100	180	41.65	6.170	1140	0.422	6.10	5.677	20.52	7.6
4	100	340	45.96	5.591	1140	0.382	6.10	5.717	38.76	7.6
5	100	460	50.31	5.108	1140	0.349	6.10	5.750	52.44	7.6
6	100	580	54.22	4.739	1140	0.324	6.10	5.775	66.12	7.6
7	100	630	56.45	4.552	1140	0.311	6.10	5.788	71.82	7.6

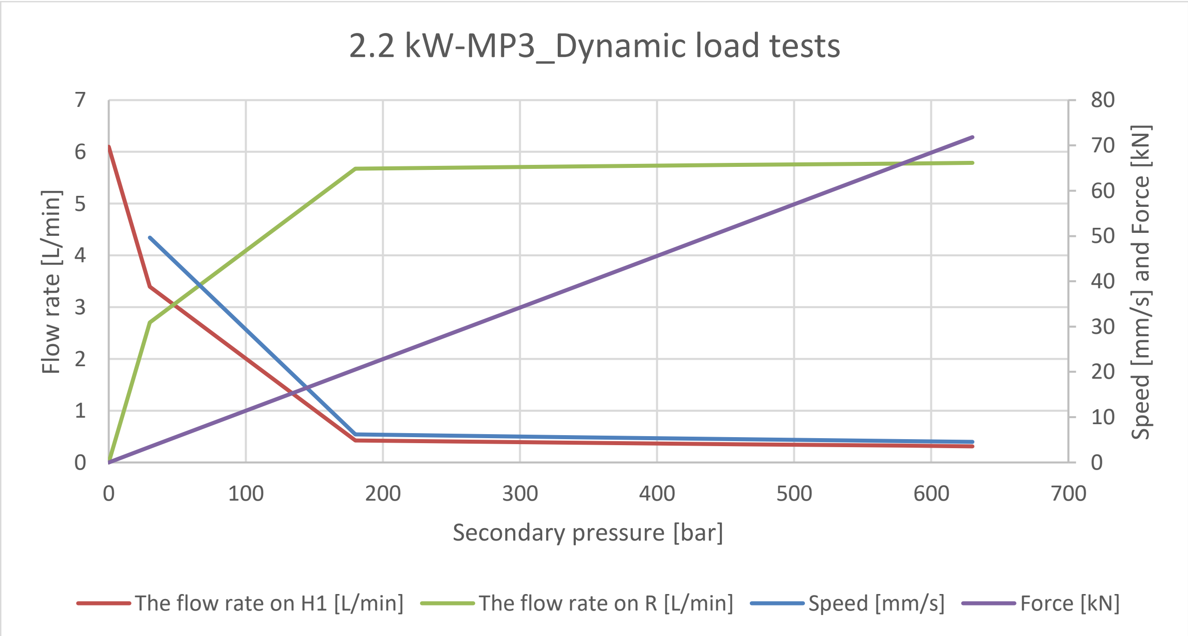


Fig. 8. Module M3: Variation of Q_{H1}, Q_R, speed, and force of test cylinder depending on p_{H1}

3.2.4 Comparison of flow rates of the pumping modules at equal dynamic loads

The three pumping modules (MP1, MP2, MP3) are characterized by increasing pressure amplification ratios (5, 6.6, 7.6) and decreasing flow rates at high pressures. As a result, the test cylinder has high speed and creates low force when it is supplied by module MP1, and vice versa, low speed and high force when it is supplied by module MP3. A comparison of flow rates at the secondary output of the minibosters of the three pumping modules (fitting **H1**), which determines the speed rates on the advance stroke of the test cylinder of the bench depending on its load, is plotted in Figures 9 and 10.

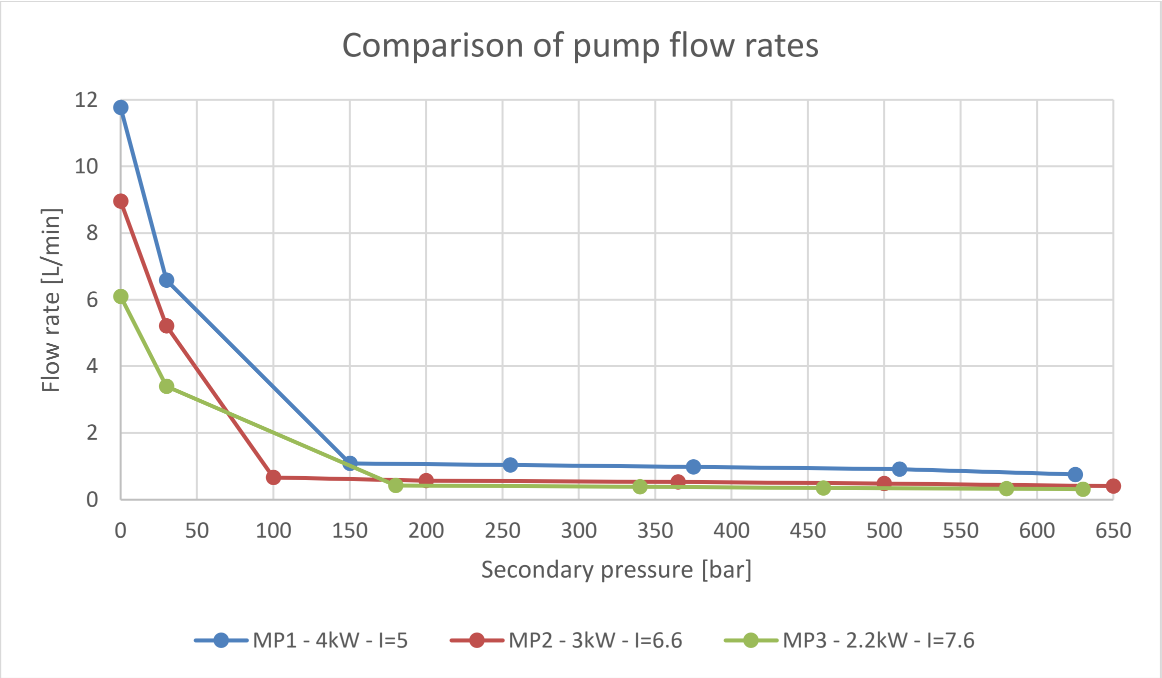


Fig. 9. Comparison of dynamic load flow rates of the three pumping modules

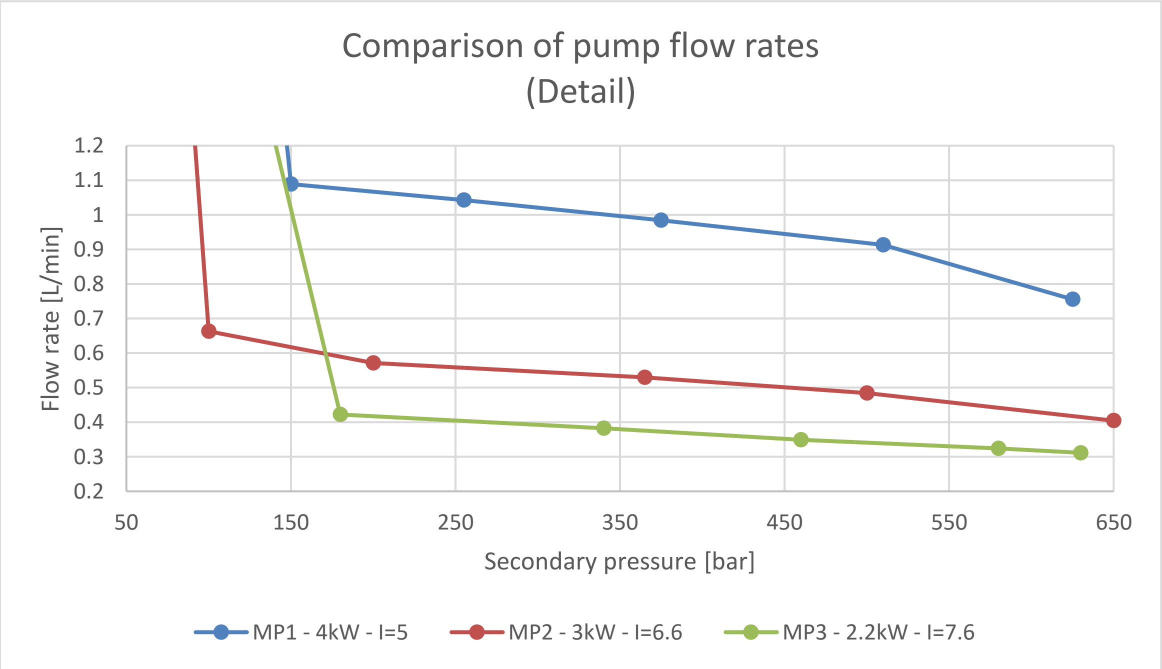


Fig. 10. Comparison of dynamic load flow rates of the three pumping modules (Detail)

4. Conclusions

- *Static load tests* have shown the ability of the pumping modules to achieve, on the high pressure fitting within the secondary side of the oscillating hydraulic amplifier, high, adjustable, static pressures (MP1 = 0 ... 1000 bar; MP2 = 0 ... 1320 bar; MP3 = 0 ... 1420 bar) through the direct pressure control valve in the primary side. This technical characteristic of the three pumping modules makes them recommendable for use in *static resistance tests of metal pipes and tanks; long-term maintenance of high pressure in hydraulic presses*.
- *Dynamic load tests* have shown the ability of the pumping modules to drive single and double acting hydraulic cylinders, of high pressures and small dimensions, on their entire advance stroke, the displacement being relatively uniform and continuous, with small pulsations*.* This technical characteristic of the three pumping modules makes them recommendable for use when driving hydraulic cylinders in the structure of *extrication rescue equipment and intervention tools used in case of road accidents; installations for lifting and getting back on the rails the derailed rolling stock; hydraulic lifting equipment used in mines and other narrow spaces.*
- *Dynamic load tests* have shown that the set of low-pressure (**LP** in Fig. 1) and high-pressure (**HP** in Fig. 1) pistons, together with the hydraulically controlled bistable distribution valve (**BV1** in Fig. 1) oscillates inside minibosters even if there is only the resistive load given by internal frictions in the seals of hydraulic cylinders of the bench (approx. 30 bar on output **H** of the miniboster). For such low loads, the flow rates on return **R** of the minibosters being appreciable (5.186 l / min, for module M1; 3.743 l / min, for module M2; 3.420 l / min, for module M3), the displacement speeds of hydraulic cylinders decrease significantly compared to the case when they are supplied with a pumping module without minibooster.
- For a qualitative assessment of uniformity of displacement of the hydraulic cylinders in the structure of the bench, measurements will be carried out by using an acceleration transducer fixed on the coupling between the rods of the cylinders.

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