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METHOD AND MEANS OF MEASURING PULSATING FLOWRATES OF OSCILLATING HYDRAULIC PRESSURE INTENSIFIERS

Teodor Costinel POPESCU[1,*], Alexandru-Polifron CHIRIȚĂ[1], Krzysztof NIEŚPIAŁOWSKI[2], Ana-Maria Carla POPESCU[1]

[1] National Institute of Research & Development for Optoelectronics/INOE 2000, Subsidiary Hydraulics and Pneumatics Research Institute/IHP, Bucharest, Romania

[2] KOMAG Institute of Mining Technology, Gliwice, Poland

* popescu.ihp@fluidas.ro

Abstract: *Oscillating hydraulic pressure intensifiers (miniboosters), which consume low pressures at high flowrates to supply high pressures at low flowrates to hydraulic (linear and rotary) motors, have a pulsating mode of operation. The flowrate of the pumping units equipped with such intensifiers must be measured with a device compatible with this operating regime. The compatibility of the device assumes the absence of moving inertial masses and a rapid response to flowrate variations caused by pressure variations. The authors designed such a device, which comprises a differential pressure transducer, connected to two pressure intake ports, mounted upstream and downstream of a calibrated orifice. Dimensioning the calibrated orifices, designing the device and optimizing its performance were carried out with Simcenter Amesim numerical simulation software.*

Keywords: *Low pressure, minibooster, high pressure, pulsating mode of operation, calibrated orifice, differential pressure transducer*

1. Introduction

An oscillating hydraulic pressure intensifier [1,2,3] works like a small piston pump that has different active surfaces (Fig. 1). In a static hydraulic system, it will supply a smaller and smaller flowrate until the pressure at its outlet, required by the system load, is reached.

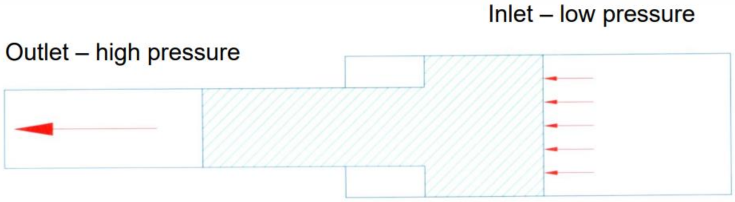

Fig. 1. Minibooster operation assimilated to piston pump operation

The pumping unit in Fig. 2, consisting of **low-pressure electric pump,** 4/2 **hydraulic directional control valve**, electrically-operated, and **minibooster**, supplies a single acting and spring-return hydraulic cylinder.
On the **extension stroke** of the cylinder rod, oil enters the piston chamber, which increases its volume. The piston of the minibooster, which works like a piston pump, is hydraulically actuated **S** with the **PCV** slide valve. It moves alternately left and right, generating the variable volume chambers **V1**, **V2**, and supplies the hydraulic cylinder with a pulsating flowrate, thus: in the **suction** phase, the hydraulic oil pushed by the **low-pressure** pump opens the **CV1** check valve and **fills** the **V2** volume chamber; in the **discharge** phase, the hydraulic oil at **high pressure** in the **V2** volume chamber opens the **CV2** check valve and supplies the hydraulic cylinder.
On the **retraction stroke** of the cylinder rod, the oil in the piston chamber, which decreases in volume, is drained to the tank, through the **PDV** unlockable check valve, controlled by the low-pressure pump.

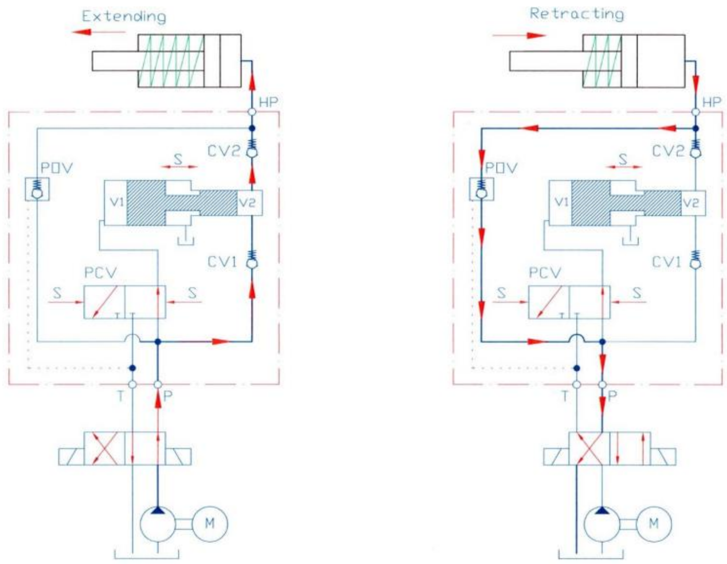

Fig. 2. Supplying a hydraulic cylinder with a pumping unit equipped with a minibooster

Static applications of pumping systems equipped with miniboosters (high pressure resistance tests for pipes and tanks, achieving high pressing or tightening forces) are not influenced by the pressure and flow pulsations (oscillations) at the output of the minibooster [4]. For **dynamic applications**, with hydraulic cylinders moving with high load, constant or variable, over the entire stroke, pressure and flow oscillations at the output of the minibooster can disrupt the uniformity of the displacement of the hydraulic cylinder connected to that minibooster [5].
The pulsating flowrate measuring device covers the range of three HC7 miniboosters, with intensification factors **5.0**, **6.6** and **7.6**, presented in Fig. 3 and Table 1 [6]. All these miniboosters are supplied at the inlet port with a flowrate of approx. **10.5 l/min**, supplied at **200 bar** by a low-pressure pump.

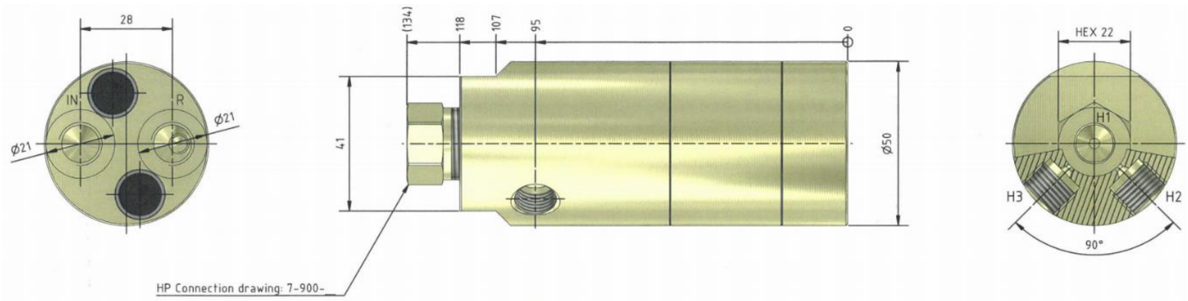

Fig. 3. Dimensions of the HC7 minibooster

Table 1: Technical features of the HC7 minibooster

Intensification factor i [-]	Primary pressure / Secondary pressure [bar]	Maximum flowrate in the primary [l/min]		Maximum flowrate in the secondary [l/min]		Dimensions of the primary connections		Dimensions of the secondary connections	
		Catalogue	Used	Catalogue	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

The uniformity of the displacement of a cylinder under load, supplied with an oscillating flowrate provided by one of the miniboosters from table 1, can be assessed on the stand [7] in Fig. 4, having the hydraulic diagram shown in Fig. 5.

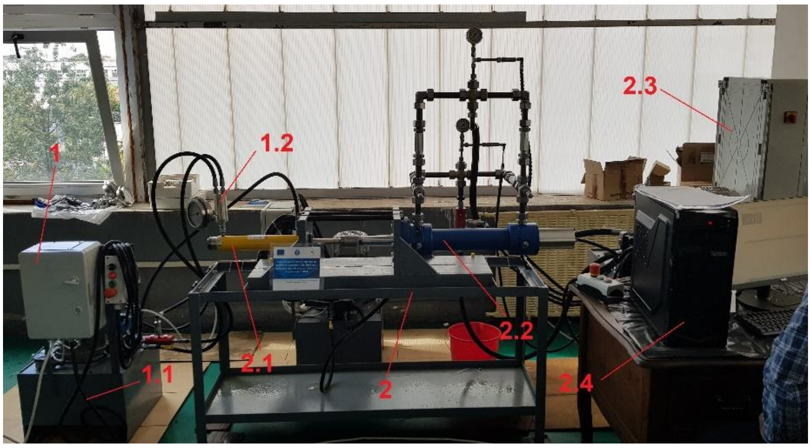

Fig. 4. Test stand for pumping units equipped with miniboosters:
1=high-pressure pumping system (HPPS); **1.1**=low-pressure pumping group; **1.2**=minibooster; **2**=test stand for HPPS; **2.1**=high pressure test cylinder (TC); **2.2**=load cylinder (LC); **S_{cs} / S_{cp}=4.4**; **2.3**=pumping unit for LC filling; **2.4**=system for stand control and experimental data acquisition.

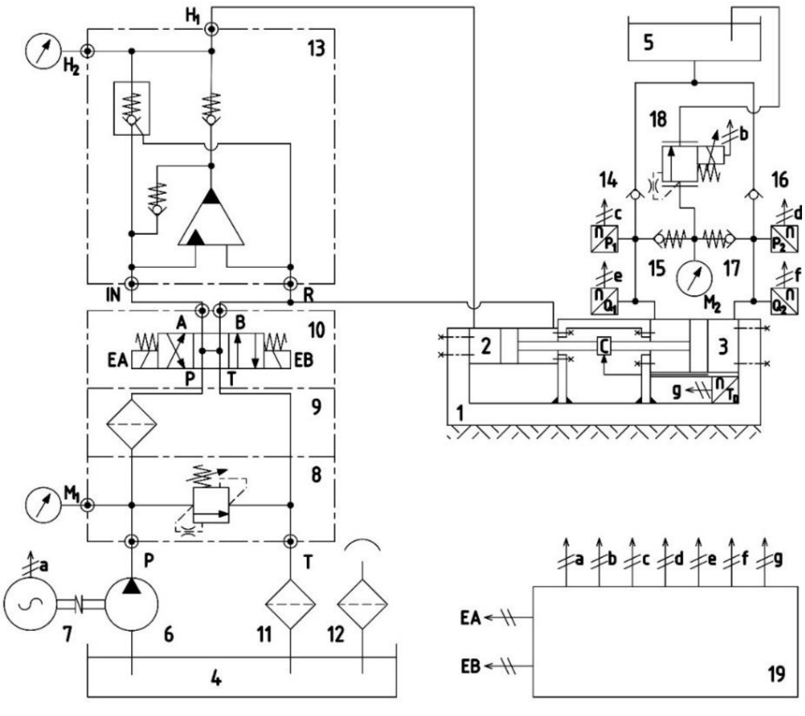

Fig. 5. Hydraulic diagram of the test stand for pumping units equipped with miniboosters:
1=hydraulic cylinder fixing frame; **2**=test cylinder TC; **3**=load cylinder LC; **C**=coupling; **4**=oil tank; **5**=oil tank; **6**=low-pressure pump; **7**=electric motor; **8**=pressure control valve; **9**=pressure filter; **10**=open-center 4/3 hydraulic directional control valve, electrically-operated; **P**,**T**=ports for pressure and directional control valve tank; **A**,**B**=ports for directional control valve consumers; **11**=return filter; **12**=fill / vent filter; **13**=minibooster; **IN**,**R**,**H**=inlet, return and minibooster high pressure ports; **14**,**15**,**16**,**17**=check valves; **18**=load pressure control proportional valve; **19**=electrical control and data acquisition panel; **EA**,**EB**,**a**,**b**=electrical control signals to directional control valve, pump drive motor and proportional valve; **c**,**d**,**e**,**f**,**g**=data acquired from pressure (**P1**,**P2**), flow (**Q1**,**Q2**) and displacement (**T_D**) transducers.

2. Numerical simulation of the operation of the flowrate measuring device

Measuring of the pulsating flowrate will be carried out successively, on two hydraulic circuits (the stand in figs. 4 and 5):
a) high-pressure ***circuit H1*** in the secondary of the pressure intensifier, which supplies the ***hydraulic test cylinder*** (2); on this circuit, the flowrate varies between the value of approx. ***10 l/min***, that is the maximum flowrate of the low-pressure pump, which supplies the primary of the pressure intensifier and bypasses the intensifier, and approx. ***1 l/min***, that is the maximum flowrate on the output of the intensifier, at the amplified pressure;
b) output circuit from the hydraulic load cylinder (3), namely on the circuit of the proportional pressure valve (18); on this circuit the flowrate varies from ***44 l/min***, value corresponding to the flowrate of **10 l/min** from the intensifier secondary, to ***4.4 l/min***, value corresponding to the flowrate of **1 l/min** from the intensifier secondary (the ratio of the active surfaces of the two cylinders coupled on the stand is $\mathbf{S_{cs} / S_{cp} = 80^2 / 38.1^2 = 4.4}$).
On the stand in figs. 4 and 5, the flow vs. pressure characteristic of the minibooster will be experimentally determined, Fig. 6, and flowrate will be measured indirectly, with a device consisting of a ***calibrated orifice*** and a ***differential pressure transducer***, type Protan PR3200, Fig. 7.

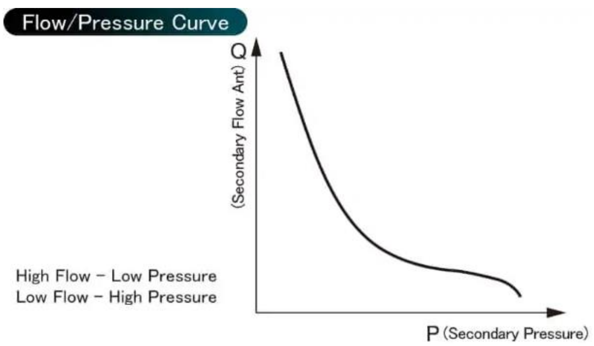

Fig. 6. Minibooster flow vs. pressure characteristic

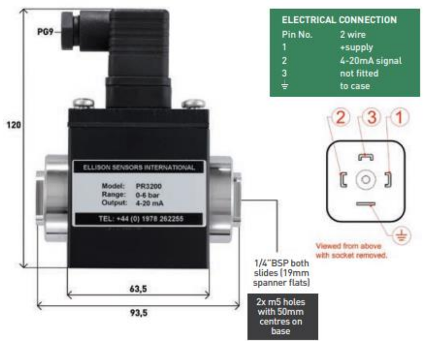

Fig. 7. PR3200 differential pressure transducer

The main technical features of the **PR3200-0100AR** differential pressure transducer are: *output signal = 4...20 mA (2 wires); supply voltage = 10...36 V d.c.; reference pressure = differential; measuring range = 0...100 bar; accuracy = ± 0.5% across the range; static pressure = 400 bar; connection to the installation = 1/4" BSP female thread.*
Knowing the **flow coefficient** of the calibrated orifice, C_Q , which is determined experimentally, **area** of the calibrated orifice, A, **differential pressure** Δp, measured with the differential pressure transducer and fluid **density**, ρ, from Bernoulli's equation, the flowrate calculation formula results:

$$Q = C_Q \cdot A \cdot \sqrt{\frac{2\Delta p}{\rho}} \qquad (1)$$

For $[C_Q] = [-]$, $[A] = m^2$, $[\Delta p] = N/m^2$ and $[\rho] = kg/m^3$, it results $[Q] = m^3/s$.

2.1 Numerical simulation model

Fig. 8 shows the device simulation network [8] consisting of: an oil ***tank***; an adjustable capacity ***pump***, driven by a 1000 rpm ***motor***; ***nine flow sections***, supplied by the pump and denoted by letters from **A** to **E'**, which effectively represent the sections on the flow path inside the flowrate measuring device; ***two pressure transducers***; ***a comparator***; an adjustable normally closed ***pressure valve*** to simulate the load. Notations in fig. 8 have the following meanings: **p1:** pressure transducer mounted upstream of the calibrated orifice; **p2:** pressure transducer mounted downstream of the calibrated orifice; **(S2): Dn10** flow sections (**C**, **C`**, **D**, **E**, **E`**), with various lengths, determined constructively from the conditions of positioning of the two pressure intake ports of the transducer and the condition of compliance with the minimum length for flow stilling; **(S1):** sections

A and **B**, which correspond to the four convergent-divergent orifices, with the role of ensuring the pressure drop needed to calculate the four flowrates.

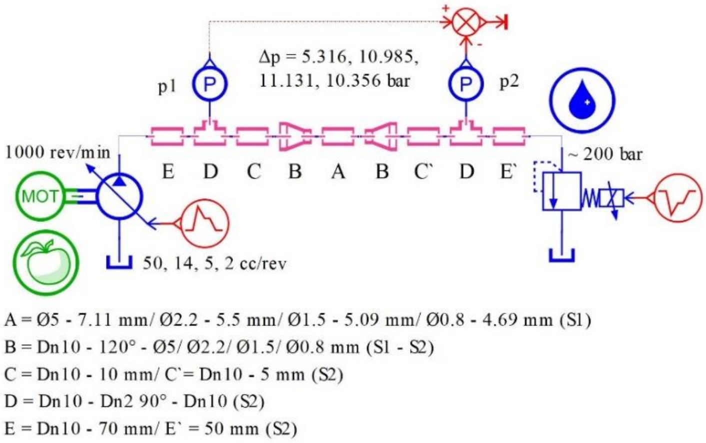

Fig. 8. Numerical simulation network in Simcenter Amesim of the flowrate measuring device

Apart from the geometric shape and lengths of the sections, the simulation also takes into account the relative roughness of the inner axial surfaces of the sections, as well as the properties of the hydraulic fluid, mentioned in Fig. 9.

Parameters

Title	Value	Unit	Tags
type of fluid properties	**advanced**		
index of hydraulic fluid	0		
temperature	40	degC	
name of fluid	unnamed fluid		
General properties			
density	850	kg/m**3	
bulk modulus	17000	bar	
slope of bulk modulus [bar] in function of pressure [bar] (in percentage)	0	null	
absolute viscosity	51	cP	
Aeration			
absolute viscosity of air/gas	0.02	cP	
saturation pressure (for dissolved air/gas)	1000	bar	
air/gas content	0.1	%	
polytropic index for air/gas/vapor content	1.4	null	
Cavitation			
(advanced user) high saturated vapor pressure	-0.5	bar	
(advanced user) low saturated vapor pressure	-0.6	bar	
(advanced user) absolute viscosity of vapor	0.02	cP	
(advanced user) effective molecular mass of vapor	200	null	
(advanced user) air/gas density at atmospheric pressure 0 degC	1.2	kg/m**3	

Fig. 9. Hydraulic fluid properties

2.2 Results of numerical simulations

With the help of numerical simulations, four calibrated orifices were dimensioned, with convergent-divergent inlets/outlets, which will be successively mounted inside the flowrate measuring device, respectively one for each of the four representative flowrates of the miniboosters in Table 1; each of these orifices provides the optimum pressure drop for the flowrate for which it was designed.

Designing of the flowrate measuring device was carried out with simultaneous observance of **three conditions:** ***pressure drop as low as possible*** on the calibrated orifice, to reduce the flowrate measurement error; ***positioning of the pressure intake ports*****,** downstream and upstream of the calibrated orifice, observing the minimum flow stilling lengths; ***ensuring laminar flow through the calibrated orifice***, namely *Re < 2300*, where the *Re* number is given by the relation:

$$Re = \frac{V \cdot l}{\nu} \tag{2}$$

where *Re* = dimensionless Reynolds number *[-]*; *V* = fluid velocity in *[m/s]*; *l* = characteristic length in *[m]*; ν = fluid kinematic viscosity in *[m²/s]*.

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The numerical simulation model in Fig. 8 **is run for four cases**, each case corresponding to a different value of the maximum flowrate of the adjustable capacity pump.
In case 1, shown in the graph of Fig. 10, a calibrated orifice is dimensioned corresponding to the measurement of a flowrate of ***10 l/min***, the maximum flowrate of the pump being set to *14 l/min*. **It results:** orifice diameter is ***2.2 mm***, pressure drop is ***10.985 bar***, and ***flow is laminar***, because ***Re = 1606***.

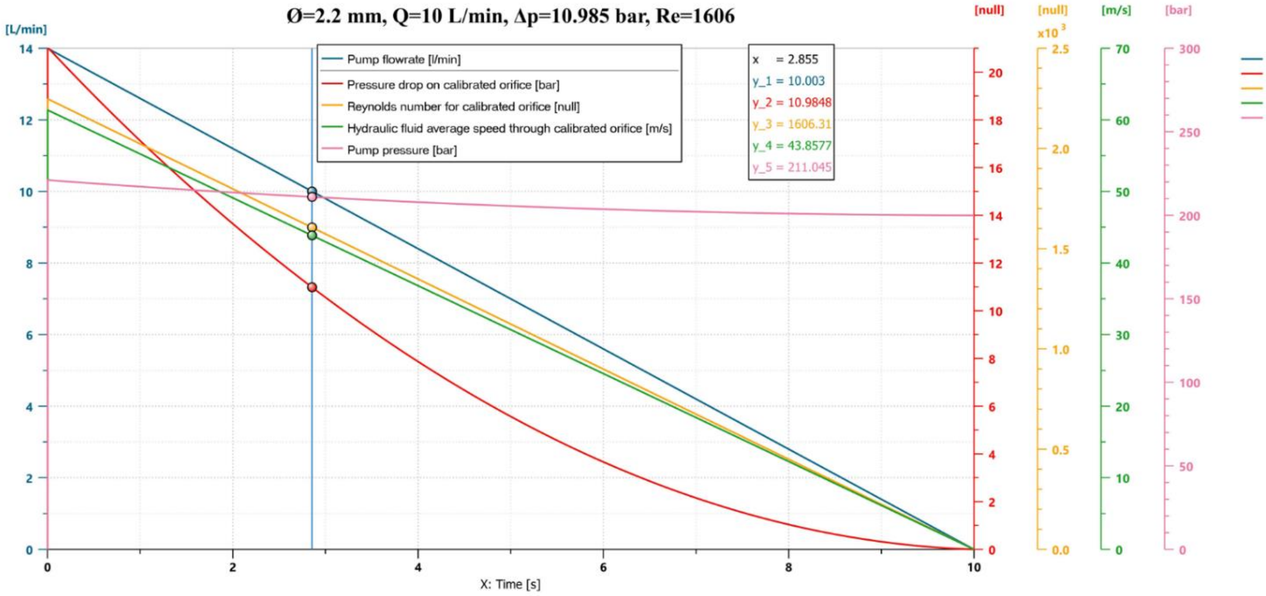

Fig. 10. Optimal dimensioning of the calibrated orifice for measuring a flowrate of 10 l/min

In case 2, shown in the graph of Fig. 11, a calibrated orifice is dimensioned corresponding to the measurement of a flowrate of ***1 l/min***, the maximum flowrate of the pump being set to *2 l/min.* **It results:** orifice diameter is ***0.8 mm,*** pressure drop is ***10.356 bar***, and ***flow is laminar***, because **Re = 442**.

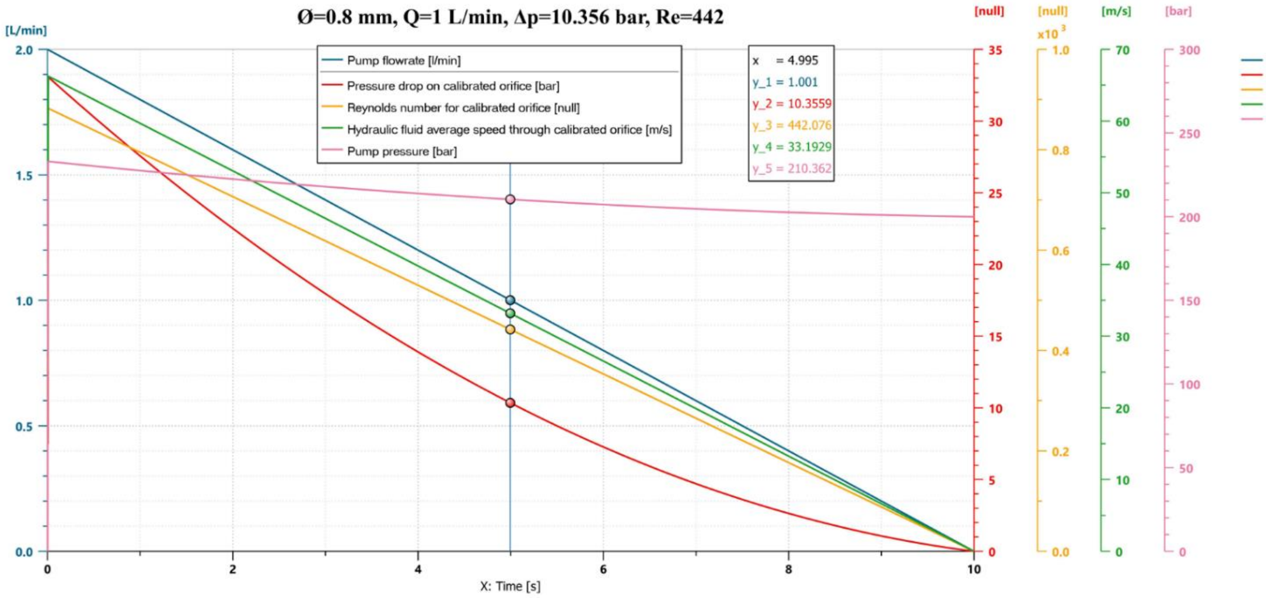

Fig. 11. Optimal dimensioning of the calibrated orifice for measuring a flowrate of 1 l/min

In case 3, shown in the graph of Fig. 12, a calibrated orifice is dimensioned corresponding to the measurement of a flowrate of ***44 l/min***, the maximum flowrate of the pump being set to *50 l/min*. **It results:** orifice diameter is ***5 mm***, pressure drop is ***5.3 bar***, and ***flow is no longer completely laminar***, because the value of the Reynolds number exceeds 2400, namely ***Re = 3110***, although measures have been taken to decrease the velocity of fluid through the orifice by increasing the diameter. However, a pressure drop of less than ***5 bar*** is not acceptable for the flowrate of ***44 l/min***, because with this orifice it is also desired to measure a minimum flowrate of ***10 l/min***, with a pressure drop of approximately ***1.4 bar***.

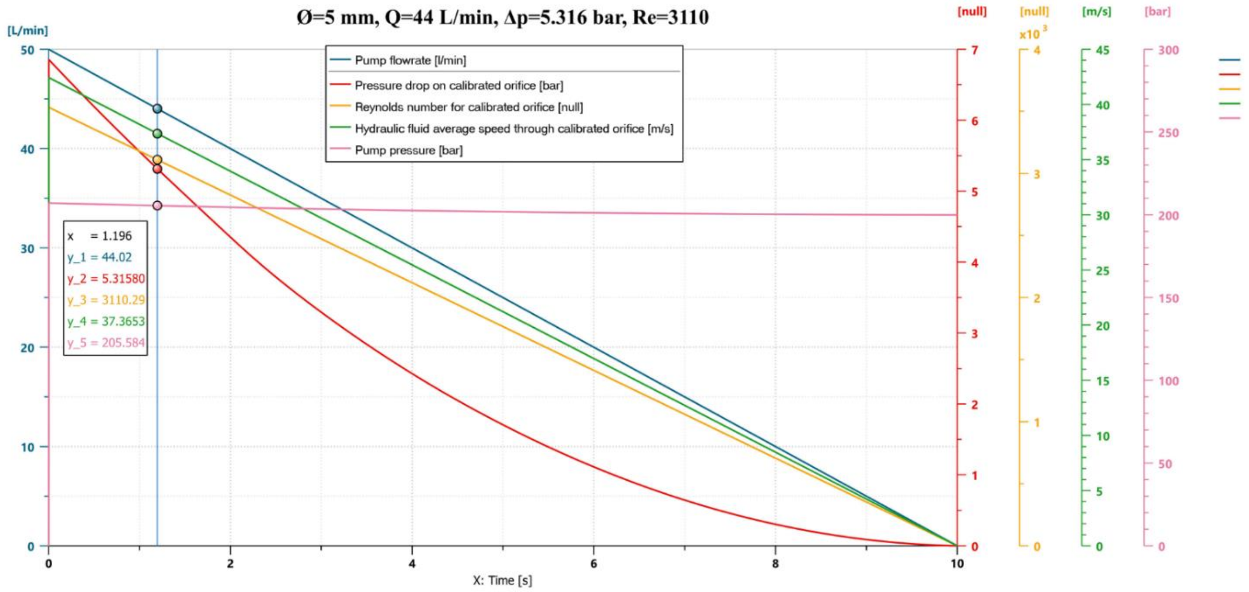

Fig. 12. Optimal dimensioning of the calibrated orifice for measuring a flowrate of 44 l/min

In case 4, shown in the graph of Fig. 13, a calibrated orifice is dimensioned corresponding to the measurement of a flowrate of ***4.4 l/min***, the maximum flowrate of the pump being set to *5 l/min*. **It results:** orifice diameter is ***1.5 mm***, pressure drop is ***11.13 bar***, and ***flow is laminar***, because ***Re = 1306***.

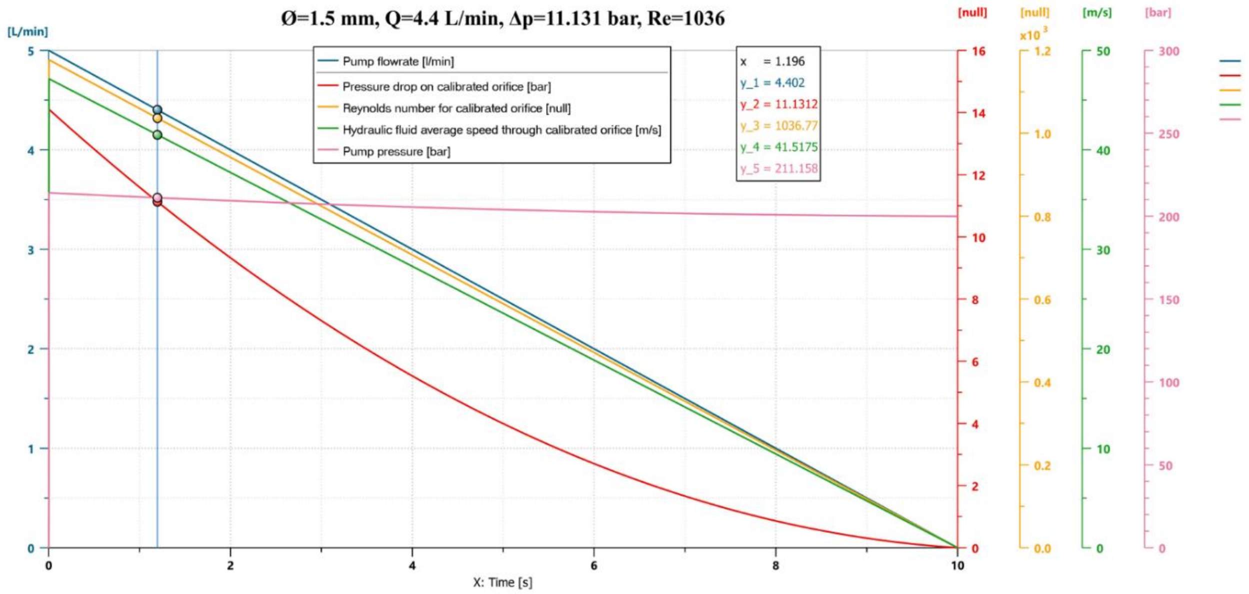

Fig. 13. Optimal dimensioning of the calibrated orifice for measuring a flowrate of 4.4 l/min

Fig. 14 shows the four calibrated orifices with diameters of ***5***, ***2.2***, ***1.5*** and ***0.8*** mm, necessary to measure flowrates in the vicinity of the values of ***44***, ***10***, ***4.4*** and ***1 l/min***. It can be noticed that all the orifices have: ***the same overall dimensions***, so that they can be mounted in the body of the flowrate measuring device; ***the same angle of 120º***, of convergence and divergence, for easy processing; ***different inner diameters***, with usual values.

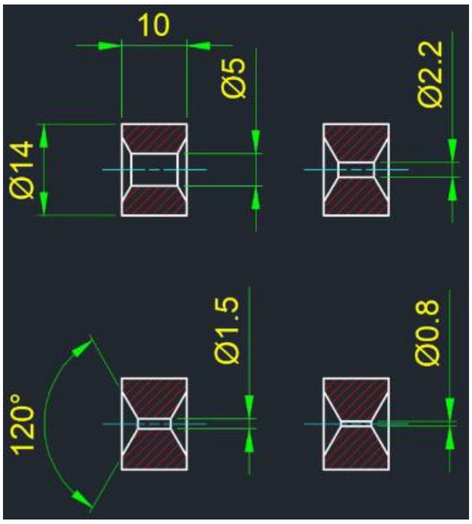

Fig. 14. The four calibrated orifices of the flowrate measuring device

2.3 Designing the flowrate measuring device

The component elements of the pulsating flowrate measuring device are shown in the assembly drawing in Fig. 15.

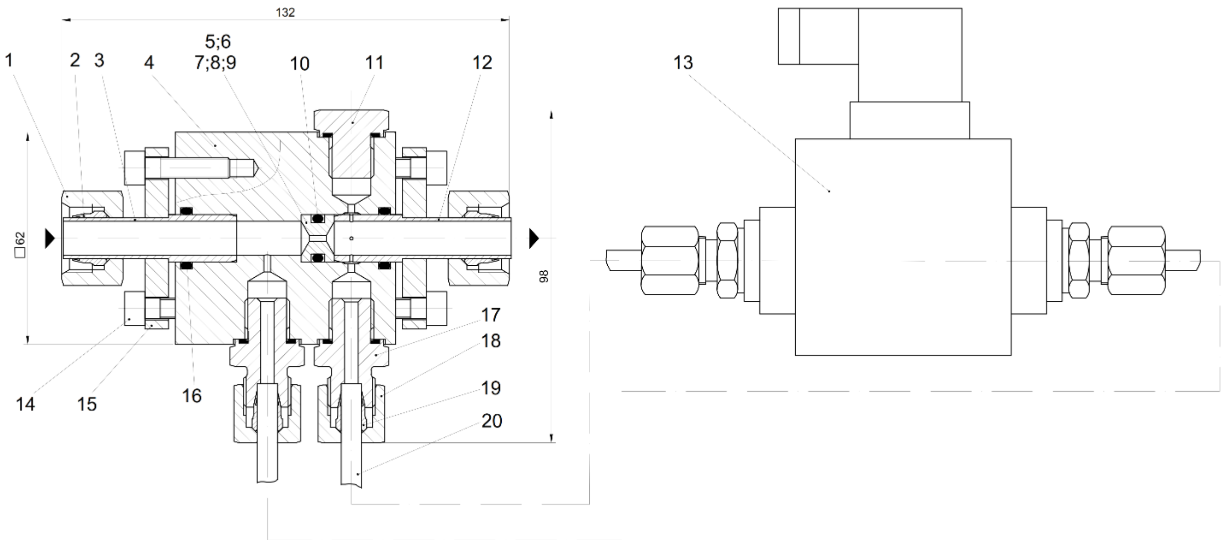

Fig. 15. Pulsating flowrate measuring device; assembly drawing

The pulsating flowrate measuring **device** contains a body, **item no. 4**, in which two pipes with a machined inner surface and an inner diameter of 10 mm are inserted into the central axial area, **item no. 3** and **item no. 12**, upstream and downstream of the calibrated orifice, respectively one of the items no. **5**,**6**,**7**,**8,** or **9**, which are sealed inside the body with one 2.5x9 O-ring each, **item no. 10**, each pipe being fixed to the body with a clamping plate, **item no. 15**, and four M6x25 screws, **item no. 14**.

The two pipes are sealed in the body with one 2.5x14 O-ring each, **item no. 16**, and on the outer end of the body, they have mounted one M20x1.5 union nut, **item no. 1**, and a cutting ring, **item no. 2**, both parts being necessary to connect the flowrate measuring device to one of the measuring circuits mentioned in section 2. The hydraulic fluid flows through the flowrate measuring device from left to right along a path with cylindrical internal geometry, nominal diameter Dn10, which is throttled in the area of the calibrated orifice.

The pressure intake ports connect to the differential pressure transducer, **item no. 13**, by means of four G1/4" threaded connections, **item no. 17**, four M14x1.5 union nuts, **item no. 18**, four cutting rings, **item no. 19** and three meters of 6x1 pipe, **item no. 20**.

Before use, the flowrate measuring device is vented, by loosening the G1/4" threaded plug, **item no. 11**, after which the tightening is done again.

The other calibrated orifices, Fig. 14, namely items no. **8**, **7**, **6,** and **5**, will be mounted in the device when it is intended to measure flowrates around the values of **44**, **10**, **4.4** and **1 l/min**.

2.4 Connecting the flowrate measuring device

The assembly drawing in Fig. 16 shows the way of connecting the pulsating flowrate measuring device to the differential pressure transducer in Fig. 7 and to the stand in Fig. 4.

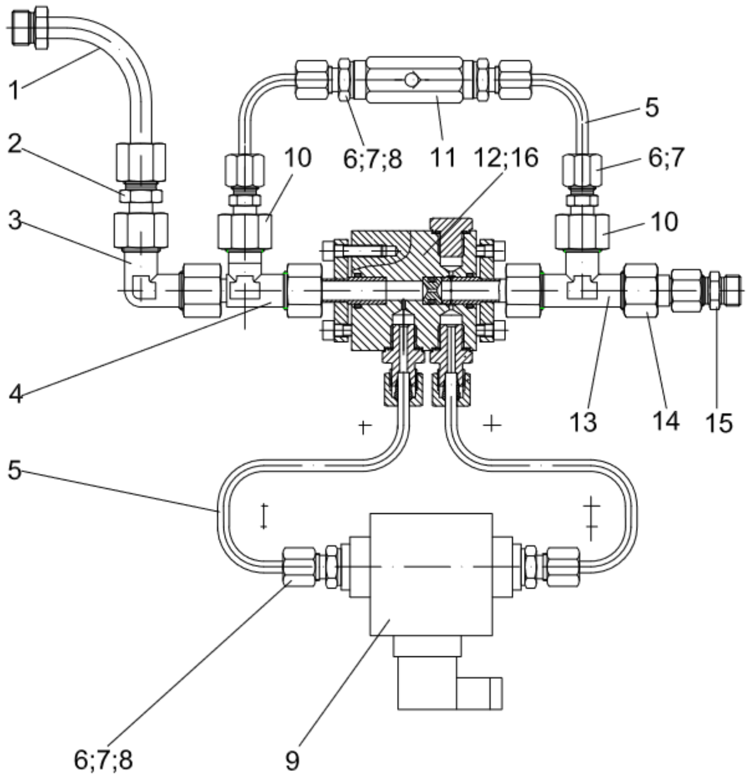

Fig. 16. Pulsating flowrate measuring device; assembly drawing for connection to the stand

The device, **item no. 12**, connects to the **differential pressure transducer**, **item no. 9**, with two 6x1 pipes, **item no. 5**, two union nuts, **item no. 6**, two cutting rings, **item no. 7**, and two G1/4-M14x1.5 threaded connections, **item no. 8**.

The device is connected to the stand in figs. 4 and 5 with a 90° pipe connection - M18-external thread / M18-internal thread, **item no. 1**, an M16/M16 nipple, **item no. 15**, an L-M20 threaded joint, **item no. 4**, an M20 T-joint, **item no. 13**.

The check valve, **item no. 11**, is mounted with two union nuts, **item no. 6**, two cutting rings, **item no. 7** and two G1/4-M14x1.5 threaded connections, **item no. 8** on a circuit that bypasses the pulsating flowrate measuring device (the device measures a flowrate only if fluid flows through it from left to right).

3. Conclusions

- ***The device is important for measuring flowrates at the output of oscillating hydraulic pressure intensifiers*** (miniboosters), under conditions where the pumping frequency of the oscillating piston is variable, decreasing as the pressure in the hydraulic system increases (fig. 6), and the ***technical documentation*** of these products ***specifies only the maximum flowrate from the secondary of the miniboosters*** (fig. 3 and table 1).
- ***When calibrating the*** flowrate measuring ***device*** the pressure difference measured between the two pressure intake ports will be taken into account, when the nominal diameter ***Dn10*** cylindrical geometry is no longer narrowed down by the calibrated orifice. This measurement will be carried out with the calibrated orifice ***Ø10***, ***item no. 9***, mounted in the flowrate measuring device.
- ***For each of the four calibrated orifices*** in fig. 14, mounted in the pulsating flowrate measuring device, one flow coefficient C_Q will be determined experimentally, as the ***ratio between the flowrate measured with a standard measuring instrument*** *(for example, graduated cylinder + timer)* and ***the flowrate measured with the presented device***. This coefficient is introduced in relation (1), for the experimental, indirect determination of the value of the measured flowrate.
- ***After developing the device***, it will be mounted on the stand in figs. 4-5, and the results of flowrate measurements for the 3 minboosters in table 1, which successively feed the test cylinder, at various loads, will be presented in a future paper.

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