Analysis of the Dynamic Behaviour and Energy Efficiency of an Oscillating Hydraulic Pressure Intensifier

PhD Stud. Eng. **Alexandru-Polifron CHIRIȚĂ*[1],** Ph.D. Eng. **Teodor Costinel POPESCU[1],** Eng. **Ioan BĂLAN[1],** Res. Assist. **Ana-Maria POPESCU[1],** Assist. Prof. **Fănel Dorel ȘCHEAUA[2]**

[1] Hydraulics and Pneumatics Research Institute INOE 2000-IHP, Bucharest, Romania

[2] "Dunărea de Jos" University of Galați, MECMET Research Center

* chirita.ihp@fluidas.ro

Abstract: *This paper presents modeling and numerical simulation of a generic single action oscillating pistons hydraulic pressure intensifier (SAOHPI), the operation mode, the analysis of the dynamic behavior of its parameters as well as the energy efficiency of a high-pressure hydraulic system comprising such an intensifier.*

Keywords: *OHPI, 2000 bar, energy efficiency, dynamic behavior, analysis, numerical simulation*

1. Introduction

There are two ways of obtaining high pressure in hydraulic systems: by using of high-pressure hydraulic pumps or by means of hydraulic pressure intensifiers. The chosen method determines the construction of a hydraulic system. When a high-pressure pump is used, all hydraulic components in the pressure line (e.g., hoses, valves, and actuator) have to be designed for high-pressure working, resulting in an increased cost of the hydraulic system. When the pressure intensifier is used, a single component, the actuator, works with high pressure, making the hydraulic system cheaper. What is more, the system with fewer component/s operating on high pressure is safer, because of lower damage probability. Using hydraulic pressure intensifier is a good solution when only the actuator/s in the system requires high pressure. [1, 2]
SAOHPIs are known in the literature under several names: oscillating hydraulic pressure amplifiers, oscillating pumping units, pressure intensifiers, boosters, mini-boosters.
Usually, these pumping units, fig.1, have in the primary an inlet connection, low pressure **IN** and an outlet connection **R** (tank), and in the secondary, an outlet connection, high pressure **H**. Structurally, they include: two joined pistons, of which one of large diameter, **LP** and another of small diameter, **HP**, the ratio of the areas of the transversal surfaces of the pistons being equal to the amplification ratio; a check valve, **KV1**, for suction of the working fluid into the high pressure chamber; other check valve, **KV2**, for discharging the working fluid from the high pressure chamber to the consumer; a **DV** unlockable check valve (for certain construction types) and a 3/2 bi-stable distribution valve, **BV1**. The position of the pistons will determine, at the end of each stroke, an **S** signal to **BV1**, which will lead to a change in the direction of travel of the piston. This cycle will continue until the final pressure is reached. At this point, the pistons stop. They will move only to maintain the final pressure. [3, 4]
These types of amplifiers operate in two phases: in the first phase, they provide consumers with an almost constant and continuous flow, equal to the maximum flow of the pump, at low pressure, and in the second phase, they provide a small pulsating flow at high pressure.
From the point of view of the pulsations of the high-pressure flow, the amplifiers with oscillating pistons can be with single action (they have higher pulsations), or with double action (they have lower pulsations).
The operating principle of an SAOHPI is as follows: a large volume at a low fluid pressure pushes a large diameter piston, into contact with another small diameter piston; as a result of this action, the small diameter piston will push a small volume of fluid, high pressure, HP, equal to the low pressure amplified with the ratio of the piston surfaces. The high pressure, HP, will always be proportional to the supply pressure of the large LP piston (if there are no internal flow losses).

In phase I of operation, on the H output of the intensifier, almost all the flow (or sheerly all the flow) given by the pump will come out at the pressure at which the safety valve is adjusted and the pistons depending on the position in which they remained previously, will move or not, then, as the load increases in the secondary, the pistons begin to move.
In phase II, the pistons will move with a frequency determined by the pump flow and the primary volume, under the control of BV1, until the maximum pressure of the amplifier is reached, after which they will stop.
If there is a pressure drop on the amplifier secondary, the pistons will restart, in order to restore the pressure to the consumer.

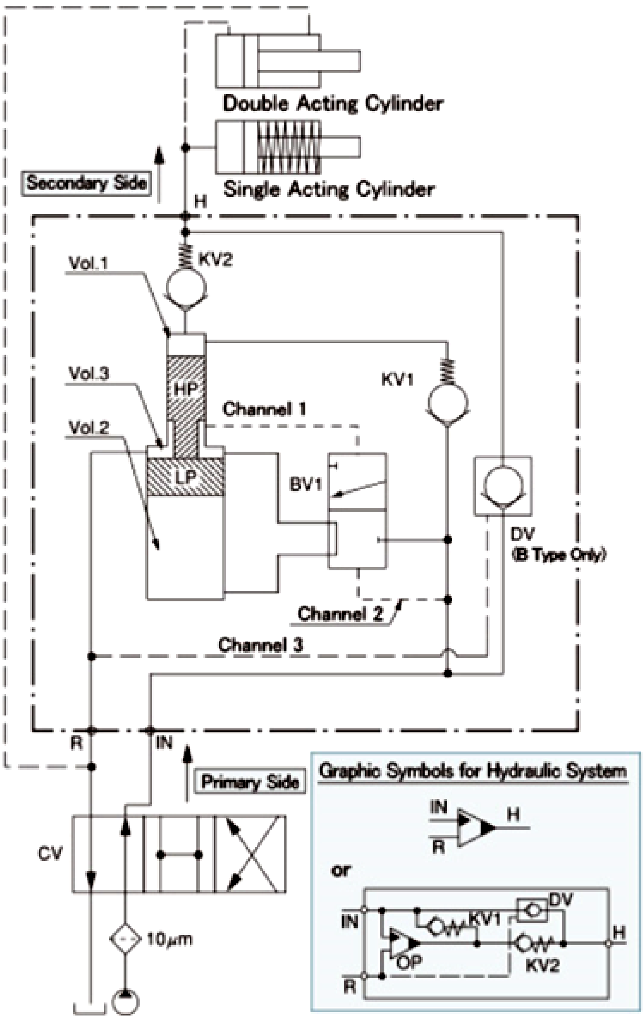

Fig. 1. SAOHPI - hydraulic diagram and functional constructive details [5]

2. Numerical simulation of a generic SAOHPI

With the Simcenter Amesim v2021.1 numerical simulation software, the physical simulation model of an SAOHPI was developed, and it is presented in fig. 2.
In the lower part of the simulation network, the one that supplies the intensifier primary, the following components can be identified: the electric motor that has a speed of 1500 rev/min, a hydraulic pump with gears, with a capacity of 8 cc/rev, a pressure valve, with the role of a safety valve, that opens if the pressure exceeds 200 bar, as well as a power, flow and pressure transducer and a tank from which the hydraulic fluid is absorbed.
In the upper part of the simulation network, which is fed from the secondary of the intensifier, the following components can be identified: a flow, pressure and power transducer, a consumer which in this case is a throttle valve, with variable section, that is controlled by a signal, which at a certain

moment commands the closing of the hydraulic orifice, as well as the tank, where the hydraulic fluid drains.
The dotted line represents a hydraulic block and delimits the hydro-mechanical components of SAOHPI, which has the following parameters: at inlet, a flow of 12 L/min at a maximum pressure of 205 bar, at outlet, an amplification factor i=10, a flow of approx. 0.8 L/min at a maximum pressure of 2000 bar.
Its structure and internal parameters were chosen so that the operating frequency is relatively low (5 Hz), so that the physical phenomena are easy to notice.
Oscillating chamber parameters are: LP diameter 24 mm, HP diameter 7.6 mm, and a stroke length of 80 mm.
Other numerical simulation settings: start time: 0 s, final time: 2 s, print interval: 0.0001 s, number of points: 20001, sampling frequency: 10000 Hz, number of variables: 255, integrator tolerance: $1e^{-07}$.

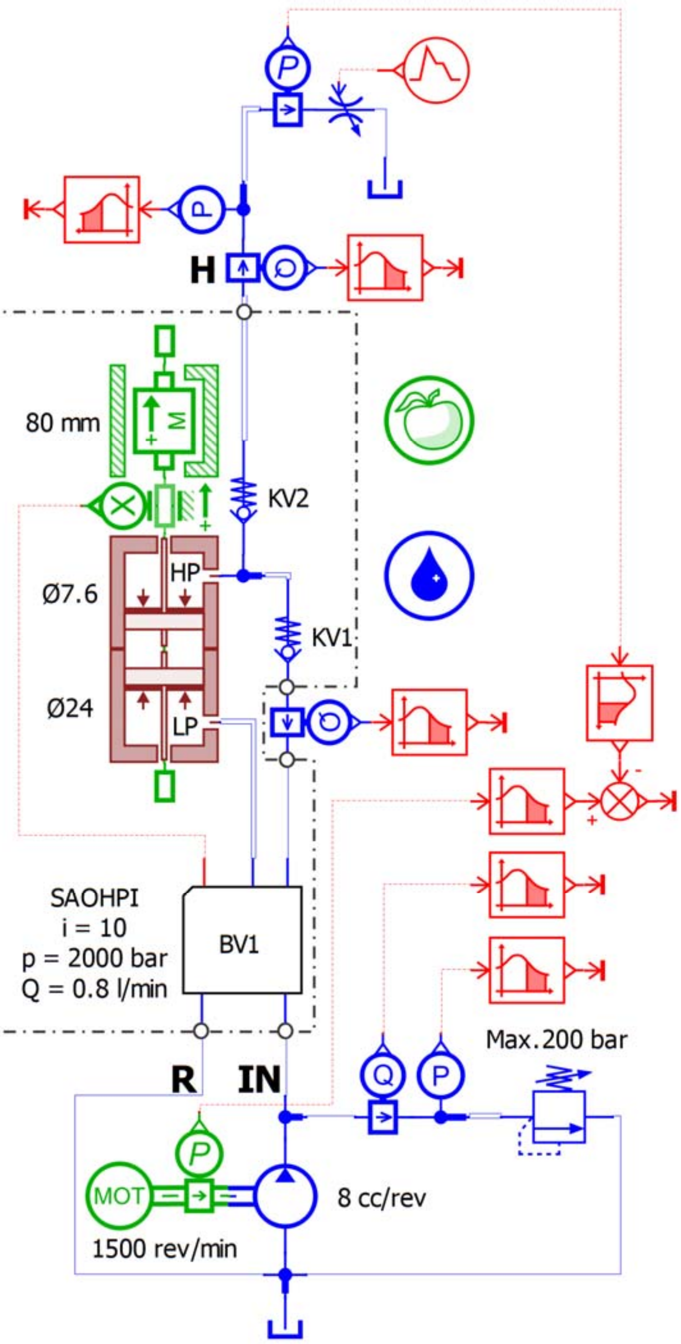

Fig. 2. SAOHPI - simulation network

2.1 Results

In this subchapter the results of the numerical simulation are presented in the form of graphs. Most of them show the evolution in time of two or even three variables on the same graph, first of all to highlight their correspondence and to save space.

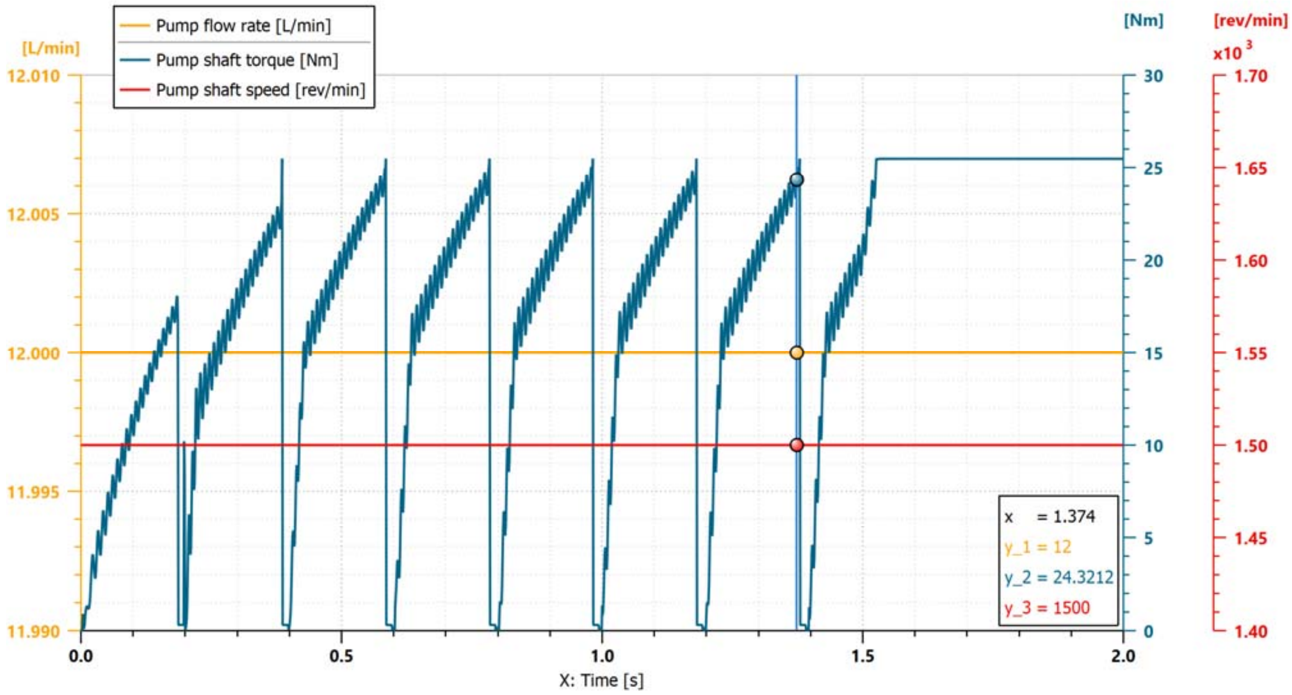

Fig. 3. Pump flow, torque and speed

Figure 3 shows the variation in time of the pump parameters, in which one can see that both speed and flow are constant; the only parameter whose evolution changes over time is torque; its variation depends on the frequency of the oscillator and the pressure of hydraulic orifice (load).

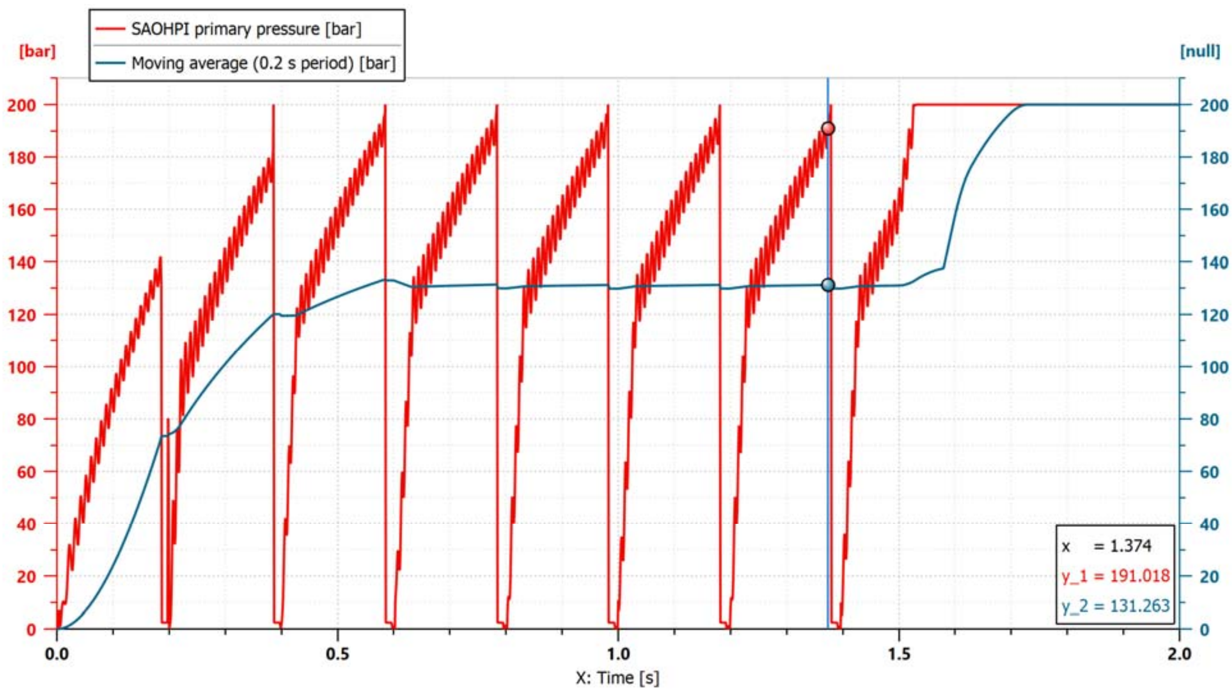

Fig. 4. Pressure in the oscillator primary

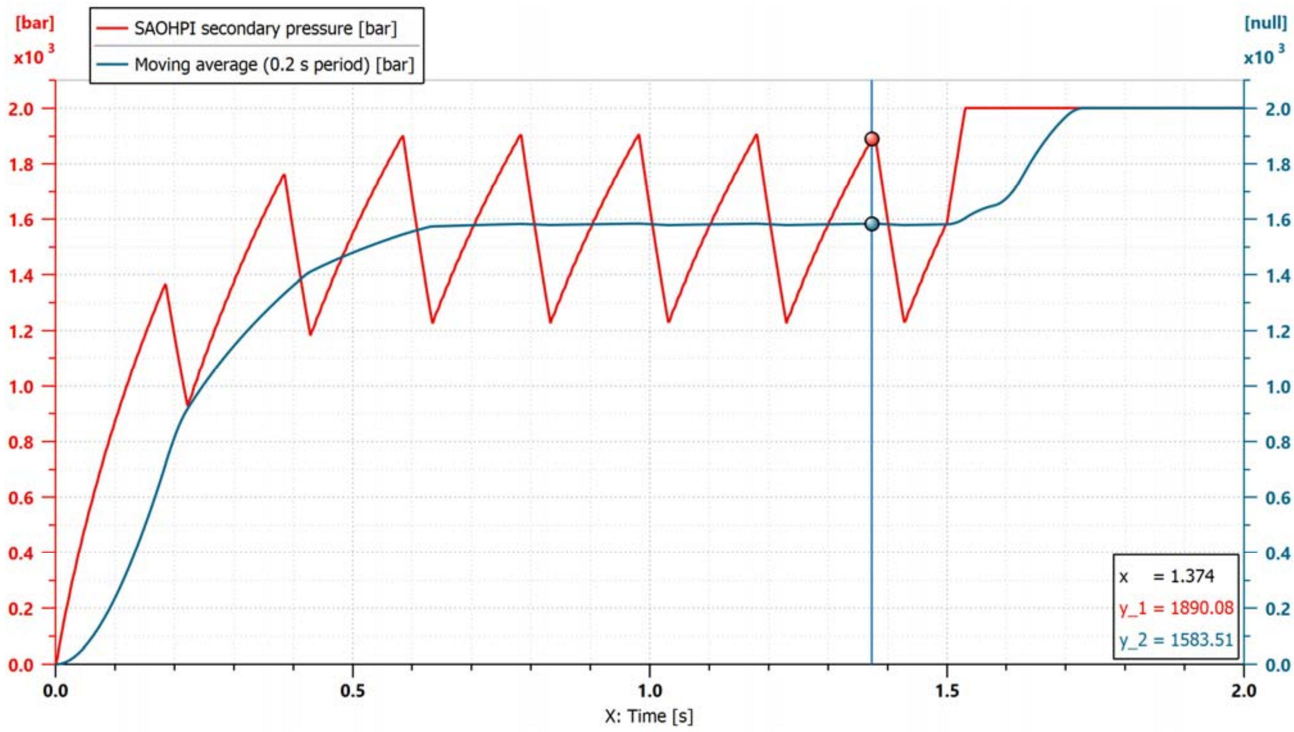

Fig. 5. Pressure in the oscillator secondary

In figure 4 and 5 one can see the evolution over time of the pressure in the oscillator primary and secondary as well as their moving average values. Also, on these graphs, one can notice the frequency of pressure pulsations in the primary and secondary of the intensifier.

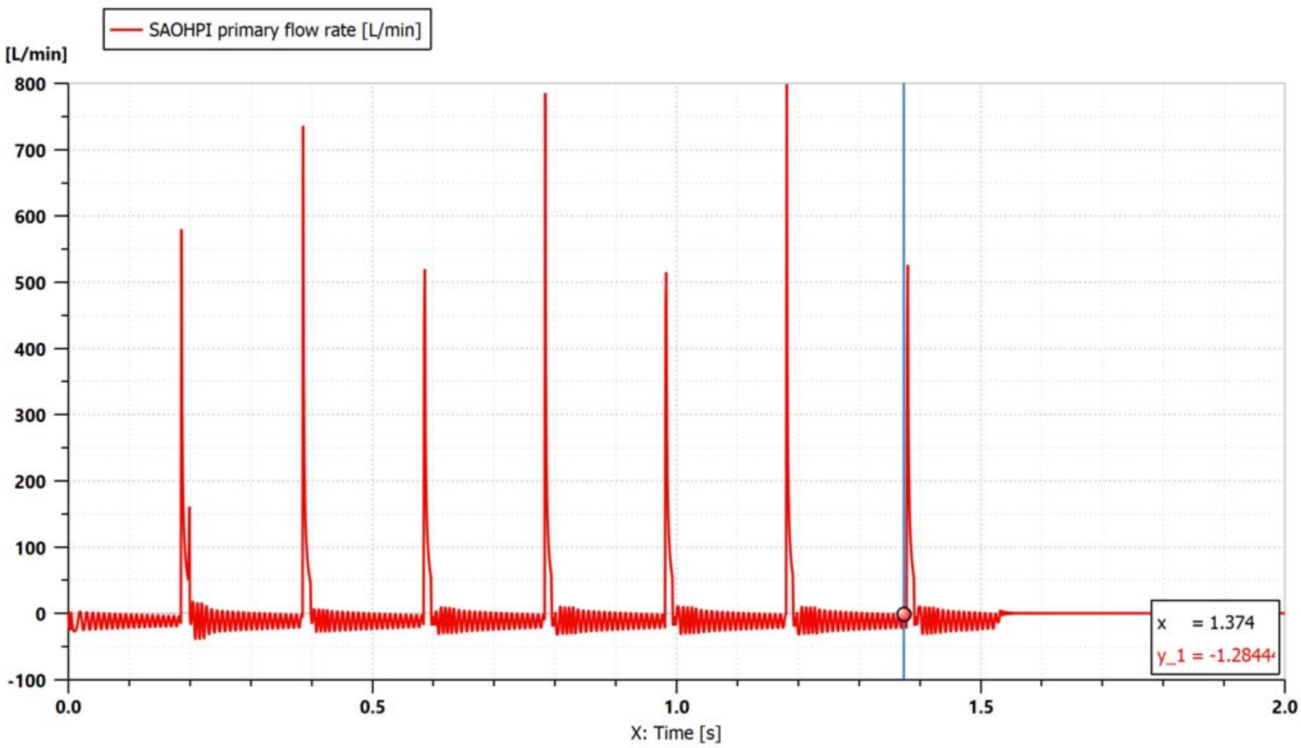

Fig. 6. Flow rate in the oscillator primary

Figure 6 and 7 show the time variation of the instantaneous flow rate values entering and leaving the two chambers of the intensifier.

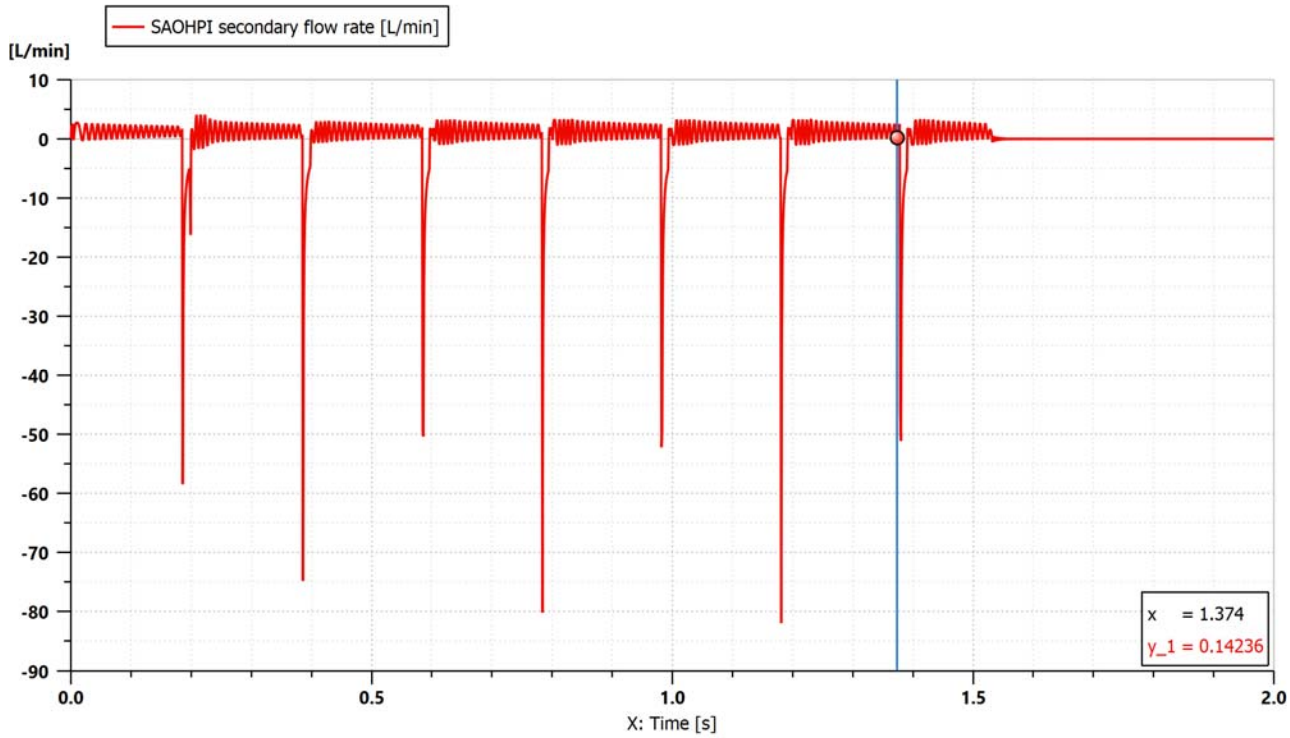

Fig. 7. Flow rate in the oscillator secondary

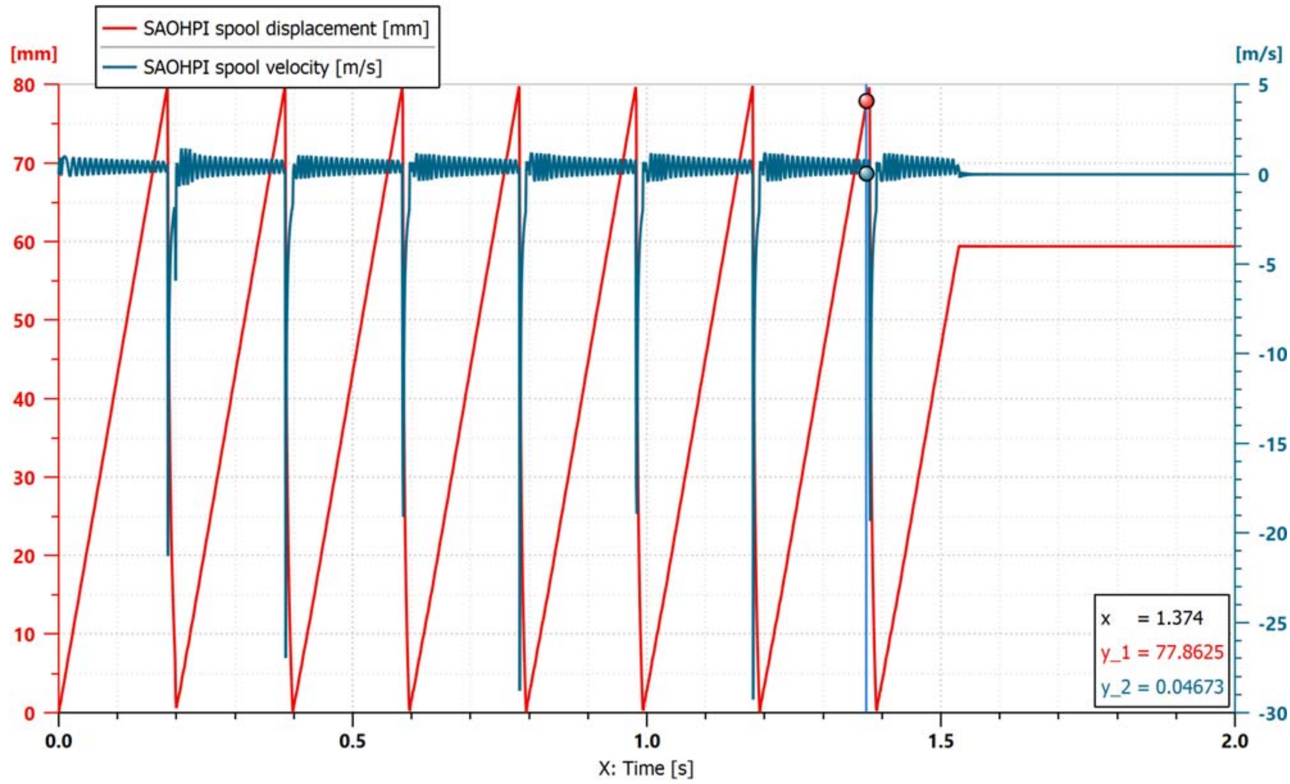

Fig. 8. Displacement and velocity of the intensifier piston

Figure 8 shows the time variation of the displacement and the displacement velocity of the piston. On this graph one can see that the displacement velocity on the active stroke is low, and on the passive stroke it is high, because all the pump flow enters the secondary chamber, which has a considerably smaller volume than the primary chamber.

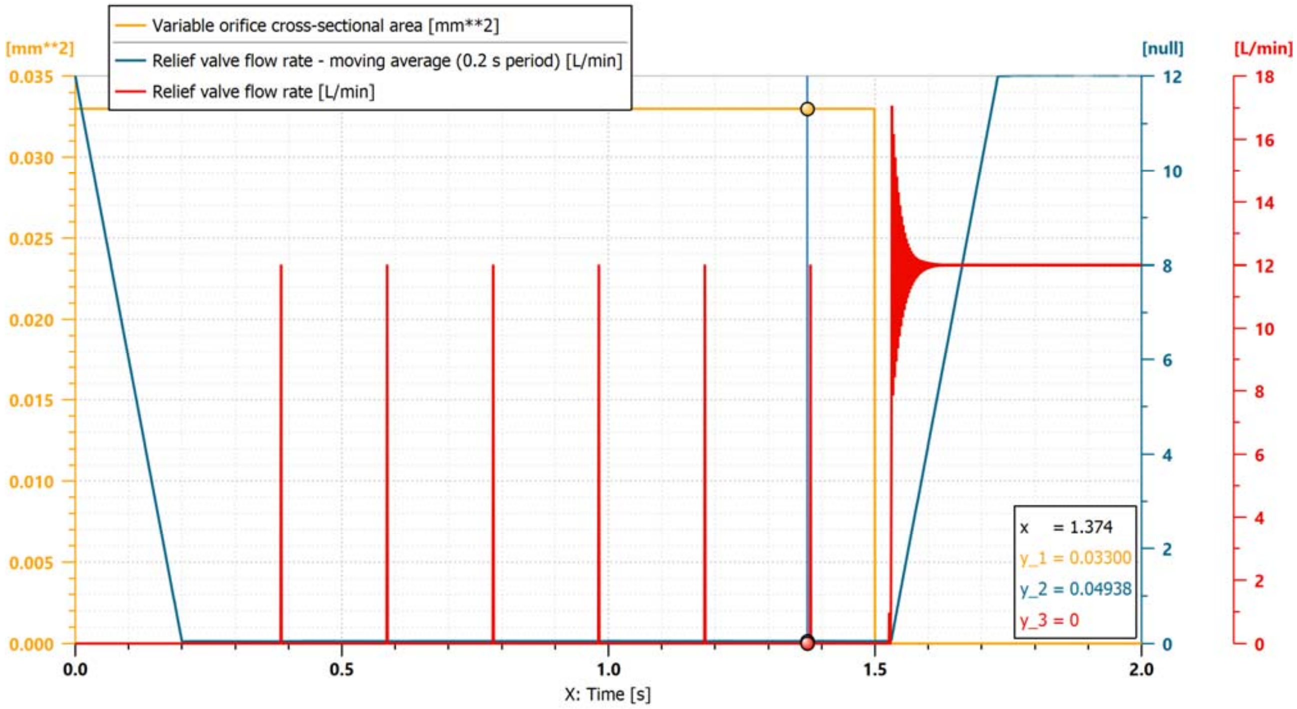

Fig. 9. The variation of the hydraulic orifice section and the flow discharged through the safety valve as well as its moving average

In the graph in figure 9 one can see that the flow section of the hydraulic orifice is open for 1.5 s, and then it is closed so that the pressure reaches 2000 bar. On the same graph one can notice the behavior of the pressure valve: it discharges a very low flow rate every time when the oscillator reaches the upper end of the stroke and changes the direction of travel; this phenomenon occurs due to the delay caused by the inertia of the oscillating piston mass, when the primary pressure reaches 200 bar and the pressure valve discharges.

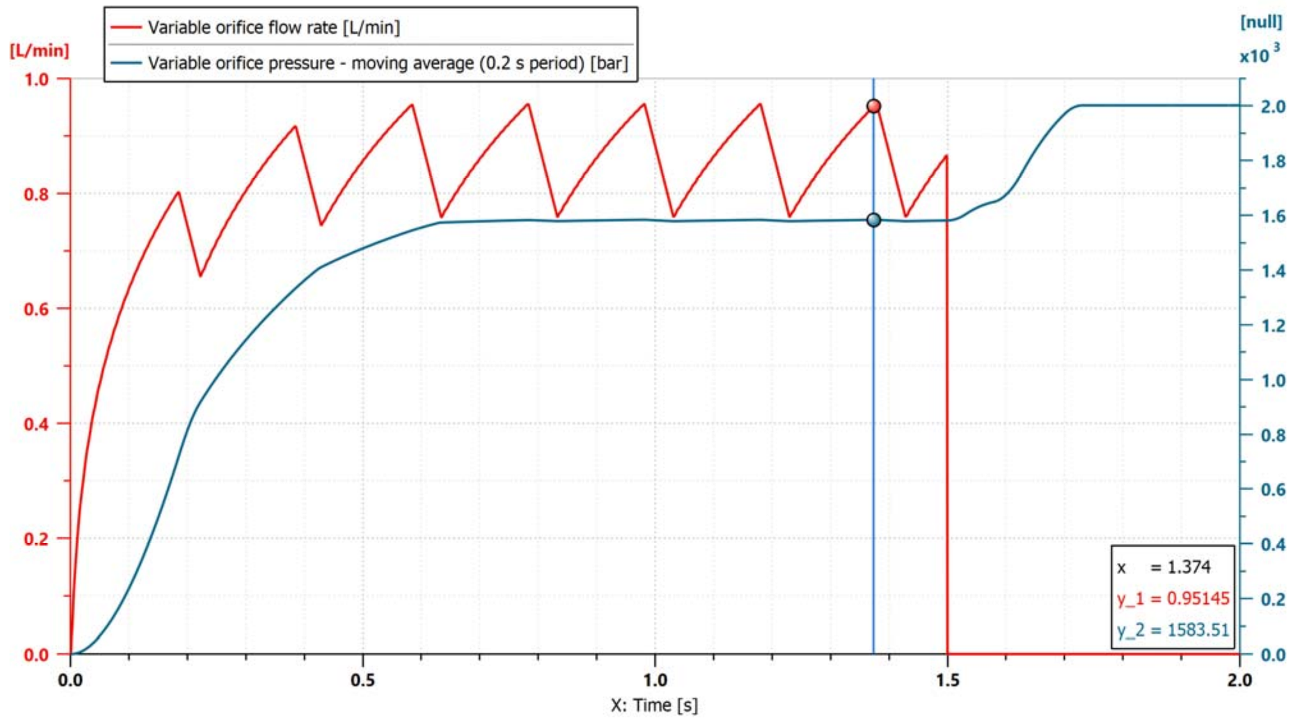

Fig. 10. Variation in time of the pulsating flow at the exit of the hydraulic orifice and the moving average of the upstream pressure

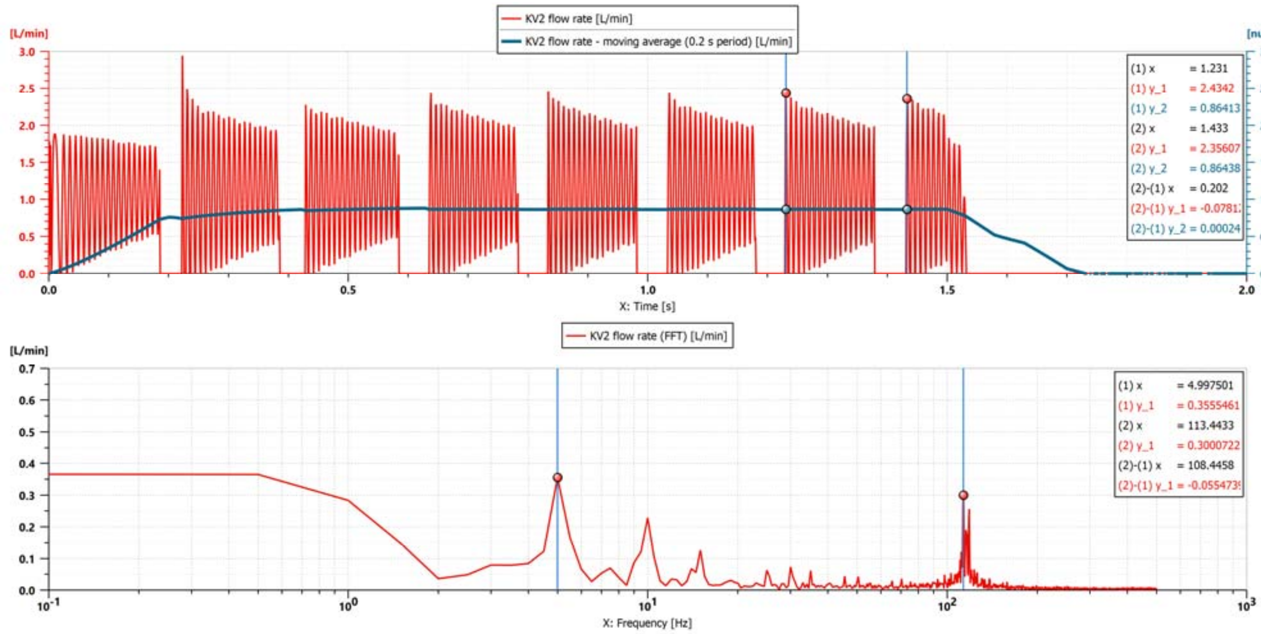

Fig. 11. KV2 flow rate, moving average and its spectrum

In figure 11, in the upper part of it, the variation in time of the flow rate of hydraulic fluid passing through the check valve KV2 is presented; the value of its moving average is 0.86 L/min. In the lower part of the figure the flow rate spectrum is presented; on it the frequencies of flow rate pulses can be identified. On this spectrum there are two notable resonant phenomena. The first phenomenon is the pumping one, with a frequency of 5 Hz and the highest amplitude of 0.35 L/min, and to its right, with a frequency of 10 Hz and 15 Hz, its harmonics can be identified. The second phenomenon, and most interesting, is located in the frequency range between 110 and 120 Hz. This resonant phenomenon is due to the inertia of the piston and the elasticity of the hydraulic system; it appears at the beginning of the piston stroke on its active side, when the value of the piston acceleration fluctuates; the only parameter of the numerical simulation that influences the frequency of this phenomenon is the mass of the piston.

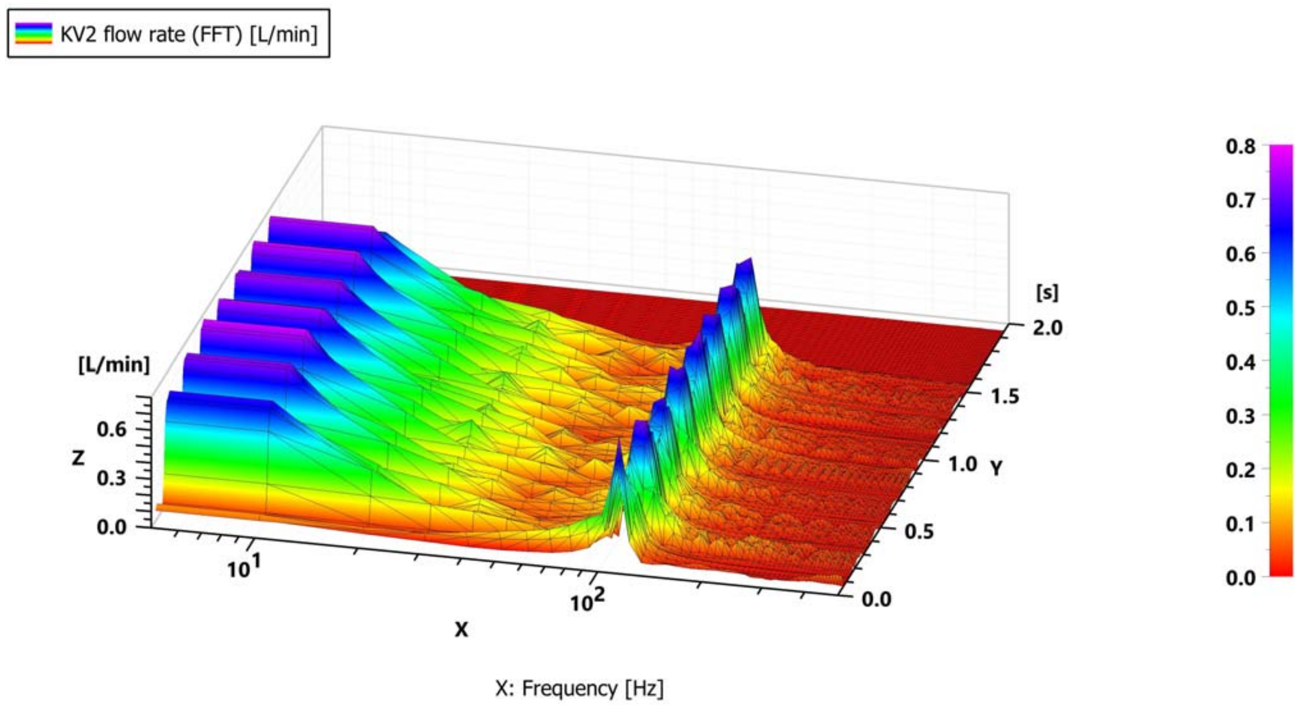

Fig. 12. Variation in time of the flow rate spectrum

The graph in figure 12 shows the variation in time of the flow spectrum; it is the same spectrum as the one in figure 11, adding a new dimension: the time on the Y axis. It was previously mentioned that certain parameters of the simulation were chosen, so that, on such a figure, the physical process is very easy to notice. In this situation, there is the diameter of the primary and the secondary (24 mm and 7.6 mm); in reality, they are much smaller and probably the piston stroke is smaller. The graph in figure 12 shows the flow variations, which can reach the consumer, when certain hydraulic components pass through resonance, when closing, opening, accelerating or decelerating their components. In the lower part of the spectrum, with a frequency of 5, 10 and 15 Hz, one can see the eight flow rates, pumped by the secondary of the intensifier; the last one is partial because the piston does not reach the end of the stroke. Another variation of the flow rate occurs in the frequency range 110-120 Hz, on the active stroke of the piston, of the pressure intensifier, when it accelerates, when leaving the place; a notable aspect is that this phenomenon occurs before the one mentioned above, which indicates that the piston moves, the secondary fluid is compressed, the compressibility of the hydraulic system dampens the piston vibration, and then the secondary flow is sent to the consumer. Other flow variations occur at: pressure safety valve with a frequency of 65, 70 and 75 Hz; KV2 - 45, 50 and 55 Hz; KV1 - 25, 30 and 35.

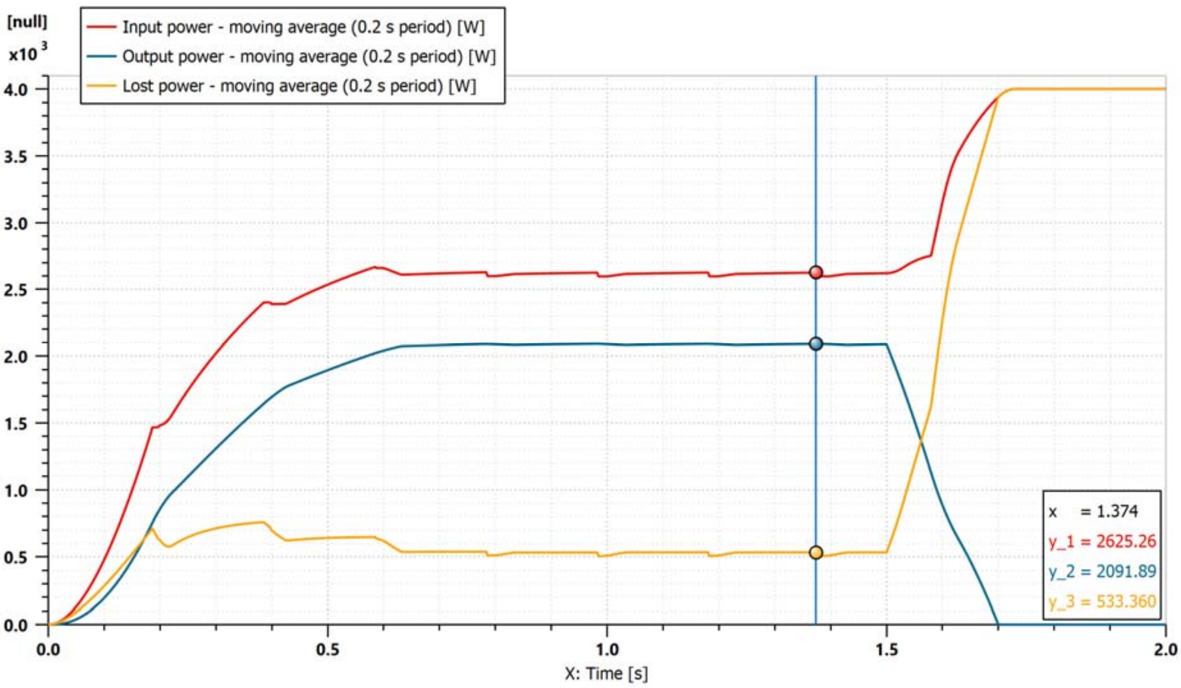

Fig. 13. Moving average of input, output and lost power

Figure 13 shows three curves, whose variation in time depicts: the power that enters the hydro-mechanical system, in red color; the useful power, which leaves the system, in blue color; and the lost power, due to flow losses to the tank, with certain pressure drops and mechanical frictions - depicted in yellow color.

3. Conclusions

- The SAOHPI is used for pressure boosting, low pressure pumping units, feeding hydraulic cylinders that linearly move large loads, anywhere on their stroke, or achieve and maintain high pressure in a closed enclosure. The SAOHPI is mounted between the pump unit and the driven cylinder, as close as possible to the latter.
- The energy efficiency of a pumping system equipped with SAOHPI is about 80%; such efficiency is comparable to that of a high-pressure pump.
- Unlike pumping systems with high pressure hydraulic pumps, SAOHPI has the following advantages: only the hydraulic circuit from the intensifier to the consumer is under high

pressure, which reduces the probability of a failure due to the small number of hydraulic components that are at high pressure; they are relatively cheap and do not require high pressure command and control equipment, and they are small in size and light.

- An important aspect to mention is that the SAOHPIs are not recommended for dynamic hydraulic drives where uniform flow rate is required, at a high pressure; due to the way they work, there are generated flow rate pulses, and between flow rate pulses there is a short time period in which the consumer is not supplied with flow rate and pressure, which causes uneven operation of the consumer.
- The amplitude of the flow rate and pressure pulses can be significantly reduced by decreasing the volume of the secondary chamber of the intensifier, but the smaller the volume of the secondary, the longer it will take the intensifier to reach high pressure.
- In order to further improve the uniformity of flow and pressure, in addition to the constructive recommendations mentioned above, a double-acting oscillating pistons hydraulic pressure intensifier can be used, which has two active strokes in the same operating cycle, unlike the SAOHPI, which has just one active stroke.

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), which is under implementation from 01.07.2020 to 30.06.2023.

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