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Experimental Determination of Pressure Losses when the Working Fluid Passes through Hydrostatic Directional Control Valves

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Abstract: *The article makes some general comments on the energy losses from hydrostatic drive system in order to increase their energy efficiency, as well as some theoretical consideration targeting the theoretical possibility of evaluating them, and in the second part of the article there is presented an experimental laboratory research to determine pressure losses when the working fluid passes through a hydraulic directional control valve commonly used in hydrostatic drives. The paper shows the schematic diagram, the experimental stand, as well as some graphical results achieved which, by comparison to the ones in the specialized literature, validate the qualitative and quantitative variation of pressure losses, and also validate correctness of the experimental testing methodology which has been used.*

Keywords: *Hydrostatic drive systems, energy efficiency, energy losses, pressure losses, flow losses*

1. Introduction

Modern hydrostatic systems are characterized by special technical performances, flexibility and low energy consumption because they are made using some modern components, with proper static and dynamic parametres, but also based on a **modern conception** in developing the schematic diagram of the hydrostatic drive. When designing them, there is performed a very careful analysis on mass and energy flow, but also on informational flow, identifying all critical points which can cause flow and pressure losses **in order to increase the energy efficiency** of the drive system.

A hydrostatic drive system consists of various components, through which the working fluid flows, and therefore this flow process through hydrostatic systems is always accompanied by **load losses**. In the design stage it is intended that these load (pressure) losses to be as small as possible, becauseall these load losses in hydrostatic drive systems implicitly lead to **high, unnecessary energy consumption**, that the power source of the equipment / machine must cover in addition to **useful consumption** that generates / ensures the required technical performances.

Load losses in hydrostatic drive systems reify in the end in **dissipating of part of the working fluid energy**, as this energy is transformed into heat energy, which is taken by the fluid, heating it, the system requiring sometimes cooling plants, which in their turn consume an extra energy to cool it. The higher **pressure drop** across each component of the hydrostatic system is, the more accentuated the above mentioned process will be.

The above presented facts are phenomena that exist and **always accompany flow phenomena** of working fluid, but the value of losses in the system should be as small as possible for **hydrostatic drive system** to be **efficient in terms of energy** [1].

That is why, when designing a hydrostatic drive system, it is necessary to use modern hydraulic components (pumps, directional control valves, motors, etc.), with high performances known from the related technical documentation, to assess, early in the design stage, pressure and flow losses, energy losses generally speaking, to guarantee high energy efficiency and high technical performances.

Worldwide one can notice intense concerns to develop hydrostatic drive systems with **power consumption as low as possible**. Since huge powers are circulated in the hydrostatic drive systems, the issue of energy consumption is particularly significant [2].

2. Some theoretical aspects regarding the flow of working fluid through hydraulic equipment

In the structure of all components of hydraulic systems, we meet, invariably, some specific elements in common: fixed or variable orifices, single or multiple: fixed or variable slits; variable **hydraulic contacts**, single or multiple [3].
A flow rate $Q\ [cm^3/s]$ passing through an **individual *hole*** of section $A\ [cm^2]$ is due to a hydraulic "tension" called pressure drop $\Delta p = p_i - p_e$ [*daN/cm²*] and is generally characterized by a law of the following form:

$$Q = C_d A\sqrt{\frac{2}{\rho}}\ (p_i - p_e)^m = k\ (p_i - p_e)^m, \tag{1}$$

where: C_d [-] = $\sqrt{1/\xi}$ at ζ = 1.8 (typical value), C_d = 0.7, and $\rho\left[\frac{daNs^2}{cm^3}\right]$ is fluid density.
If a fluid flows through a number of *n multiple* holes, in order to determine the unknown elements of flow it is necessary to solve a system of similar equations.
A flow rate $Q\ [cm^3/s]$ passing **through a slit** of some profile is also due to a pressure drop $\Delta p = p_i - p_e$, but it is generally characterized by a linear law of the following form:

$$Q = \delta\ (p_i - p_e) \tag{2}$$

δ values, for usual cases, are indicated in the literature [3].
In drive systems there also occur the so called "hydraulic contacts".
Hydraulic contacts are flow spaces between the fixed and moving parts of hydraulic devices, for example between the body and the slide valve of a hydraulic directional control valve, and they can be individual or multiple.
Individual* hydraulic contact** is characterized by a **flow law** of the form of equation (1), in which, this time, flow area *A* is a function of opening ***x of the contact, and the flow is a function not only of Δp but also of *x*:

$$Q = C_d A(x)\sqrt{\frac{2}{\rho}}\ (p_i - p_e)^m = C_d\sqrt{\frac{2}{\rho}}\ A\ (x)(\Delta p)^m \tag{3}$$

Equation (3) expresses a non-linear connection between Q, x, Δp, even if *m* would be equal to 1, due to the product between the variables *A(x)* and Δp.
***Multiple* hydraulic contact** characterizes, in fact, **hydraulic directional control valves** used in hydraulic drive systems or in automatic control systems. Unlike the single contact, in this case there occur in a single functionality **simultaneous flows through a set of contacts** connected together in series and / or parallel. To determine the relationship of interest, between the flow and pressure, of the form: $Q = f\ (x, \Delta p)$, where $\Delta p = p_i - p_m$ (and p_m= pressure drop in the driven hydraulic motor) there should be taken into account possible flows not only through the contact of the directional control valve, which connects the pump and motor input, but through all the contacts that change jointly (with the same variation of opening *x*) with the mentioned contact, upstream or downstream from it. The situations encountered in practice are numerous, and they depend on the following main factors: type of power supply (with constant pressure or constant flow), type of directional control valve (with slide valve - 1, 2, 4 active edges - or clack valve fitting), type of driven motor (differential or non-differential), slide valve type (with positive coverage, null or negative coverage, symmetric or asymmetric) [3].
***Unlinearized* characteristic equation of directional control valves** with **negative coverage** (x_a), supplied at constant pressure, figure 1, is very complicated, but it can be expressed in **the linearized form** as follows:

$$\Delta Q_m = A\ C_0 \Delta x_m + \frac{A^2 C_0}{E_0}\ \Delta p_m \tag{4}$$

where C_0 is the coefficient of flow amplification, and E_0 is the coefficient of force amplification.
Figure 2 shows a flow / working diagram through a directional control valve, 4-way, 3-position, with **positive coverage** and closed center, on this position practically flow is null, as well as pressure drops / losses. On a side position, fluid flow causes pressure loss / drop, and flow gets to the motor

/ consumer, almost entirely, except flow losses / leakages occurring through the gap between the body and slide valve / rod of directional control valve, q_{sd}, which are very low. When the fluid passes through the hydraulic rotary motor MHR, besides pressure losses / drops, there also occur internal flow losses / leakages, which go directly to the tank, but are also low.

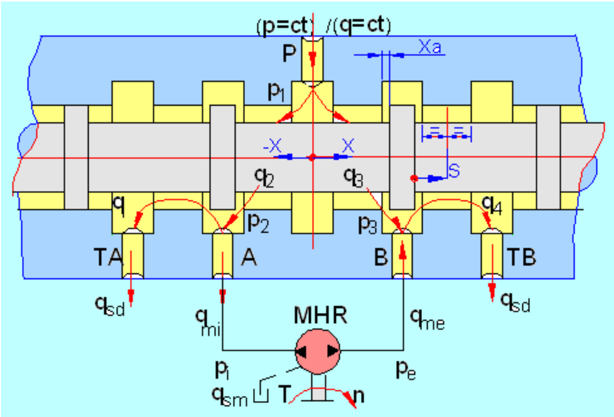


Fig. 1. Flow diagram through a 4-way open center (negative coverage) directional control valve

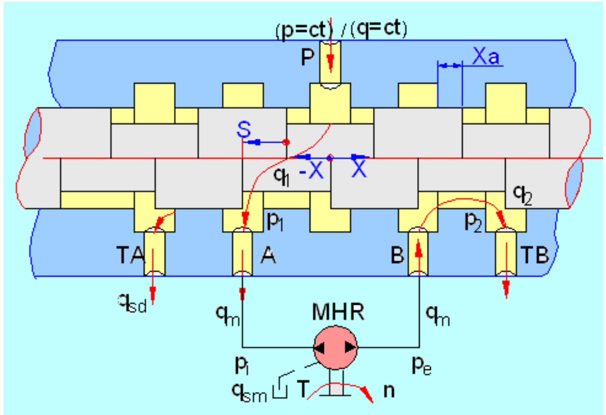


Fig. 2. Flow diagram through a 4-way, close center (positive coverage) directional control valve

As one can seen from the above, the **issue of determining theoretically** the flow flowing through a directional control valve is very complicated, in fact, the same as the issue of computing pressure losses or drops, depending on the flow which passes through the directional control valve in question. Therefore, the only accurate method for determination of pressure losses when a fluid flow circulates is the **experimental method**, which, indeed, requires adequate laboratory infrastructure. The following shows an experimental research to **determine pressure losses** as function of flow; this research has been conducted in the laboratories of INOE 2000-IHP, [4], [5].

3. Presentation of infrastructure for experimental determination of pressure losses

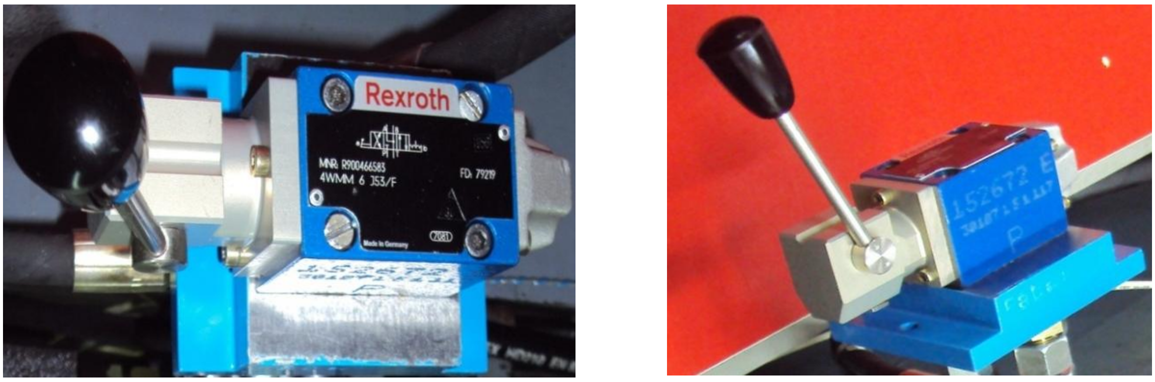
Besides lowering hydraulic drive system efficiency, losses in the system can also lead to degraded technical performances. The designer of drive systems must **identify the source of those losses** and deepen the underlying phenomena, and, even more, has to know how to limit the effects of such losses. One of the assessment methods of energy losses through different devices in the structure of hydrostatic drive systems is the experimental testing on appropriate stands. The following shows a methodology for experimental determining of pressure losses when the working fluid is passing through a hydraulic directional control valve currently used in hydrostatic drives.

3.1. The object under experimental research

As the object of experimental research there has been selected a directional spool valve, directly operated, with manual actuation, manufactured by REXROTH BOSCH GROUP company, code 4 WMM 53 6 J / F, shown in figure 3 [6]. From working diagram of the device, displayed on its label, figure 3a, there results that it is a 4-way, 3-position directional control valve; positions were obtained by manual control of the lever, having the central position with ports A and B to the tank, port P - closed. By pulling the lever, figure 3b, the result is connecting the port P to port B, this being the working position on the stand for determining pressure losses through the hydraulic directional control valve.

The main technical characteristics of the directional control valve are the following:

- Size 6, 4/3 directional design;
- Component series 5X;
- Maximum operating pressure 315 *[4569 psi*;
- Maximum flow 60 l/min *[15.8 US gpm]*;
- Types of actuation: and lever.



a) Top view **b)** Side view

Fig. 3. Directional spool valves, directly operated, with manual actuation, Rexroth Bosch Group Co. [6]

3.2. Presentation of experimental stand

To conduct the experimental research, aiming to determine the pressure losses when the working fluid passes through the hydraulic directional control valve presented, it was necessary to design and construct a test stand. The stand should make it possible to carry out imposed tests for measuring pressure at the device input, and respectively output. It also must allow flow variation in the working range of the directional control valve, having thus the possibility of recording, storing and processing the experimental data. The ultimate goal of the experimental research is to plot the variation diagram of pressure losses depending on the flow of fluid which passes through / transits the directional control valve.

Based on these requirements, there has been designed a functional diagram, shown in figure 4, based on which there has been constructed a test stand, primarily based on components existing in the Laboratory of Hydraulic Servosystems at INOE 2000-IHP, but also based on some components especially procured for that end.

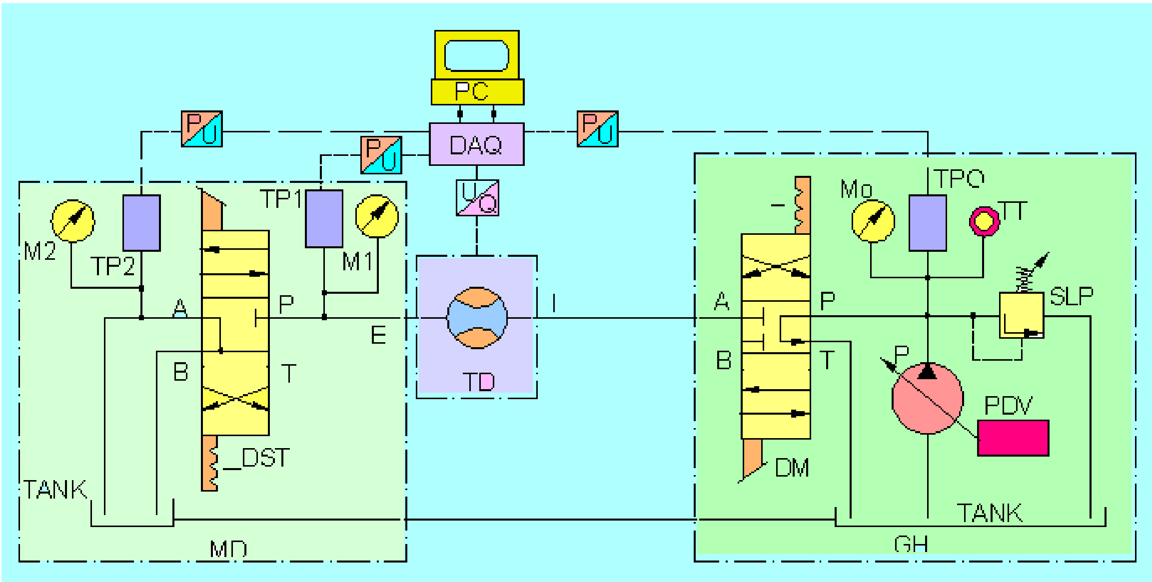


Fig. 4. Conceptual diagram of the test stand

The experimental stand consists of four main parts, namely:

- **Source / station of hydraulic power generation GH,** which consists mainly of a pump P, variable displacement, equipped with device for varying the flow PDV, assisted by a pressure limit valve SLP, flow fluid being sent to a manually operated 4-way, 3-position hydraulic directional control valve DM, on the central position the oil being returned to the tank. Oil / fluid pressure can be visually traced on a manometer M_0 and taken by the pressure transducer TP0, in order to be acquired, recorded and processed by the computer system. Oil temperature is visualized and

taken by the temperature transducer TT, in order to be acquired and registered by the computer system;
- **Module for determining the pressure losses MD**, which consists primarily of hydraulic directional control valve being tested DST, which is equipped on the inlet circuit, with a manometer M1 for viewing the oil pressure at the directional control valve input, as well as a pressure transducer TP1, for pressure signal to be taken over by the computer system. Moreover, on the output circuit, there is provided a pressure gauge M2 for viewing the oil pressure at the directional control valve output, as well as a pressure transducer TP, for pressure signal to be taken over by the computer system. After passing through the hydraulic directional control valve output, the fluid /oil reaches the second tank, which communicates, through a pipe, with the first one;
- **Flow transducer TD**, mounted between the source of working fluid generation GH and the module for determining the pressure losses MD. Flow transducer sends a signal of flow variation to the computer system, to record and process data;
- **Data acquisition, recording and processing computer system**, composed mainly of an acquisition board DAQ and a PC-type computer, and also processing **software** appropriate for the application.

Figure 5 shows a general view of the experimental stand, and figure 6 presents a view on location of the hydraulic devices that really put in practice the diagram for experimental determining of pressure losses when the working fluid passes through the directional control valve under tests.

Fig. 5. General view of experimental stand

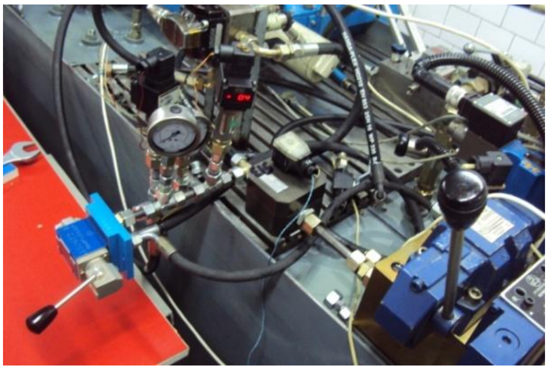


Fig. 6. View on location of hydraulic devices

A top view on location of hydraulic devices is presented in figure 7, and mounting of manometers and pressure transducers on the board of directional control valve can be seen in figure 8.

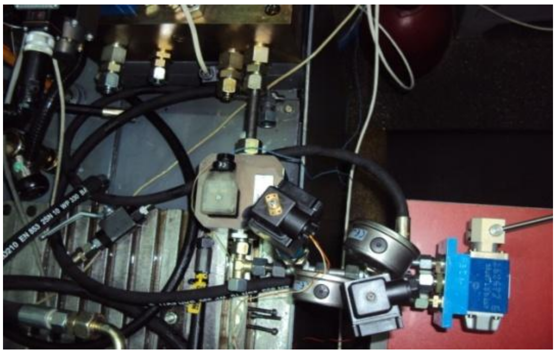


Fig. 7. Top view on location of devices

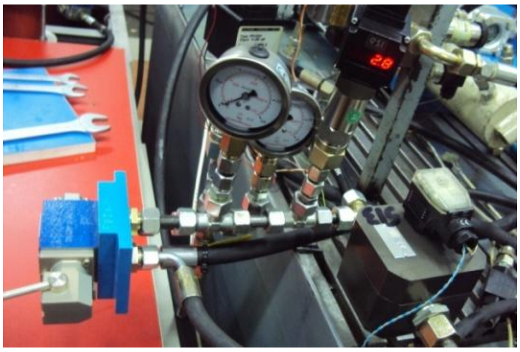


Fig. 8. Mounting of devices at directional control valve

As one could see from the description of the schematic diagram of the test stand, for the pressure, flow and oil temperature variation signals to be taken over, there have been used high performance transducers, namely: figure 9 presents pressure transducers of the type Genspec GS200, with instantaneous display of pressure value, mounted on the inlet, and respectively outlet circuits of hydraulic directional control valve, and figure 10 presents the gear flow transducer, type KZA-1865R20. Figure 11 shows both the temperature transducer manufactured by the company

TURCK and the proportional pressure control valve manufactured by the company REXROTH BOSCH GROUP.

Fig. 9. Pressure transducers with display

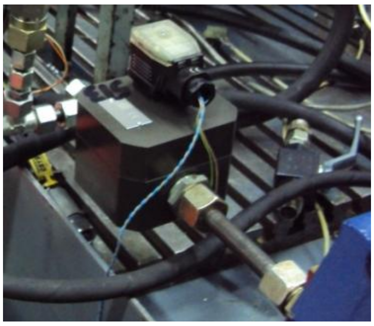


Fig. 10. Gear flow transducers

Fig. 11. Pressure transducers and pressure control valve

In order to acquire and process the signals from the transducers, there has been used **an electronic computer system**, which besides the electric panel for control, display and tracking of tested parameters, is also equipped with a PC–type computer, as one can see in figure 12, inclusively supply sources and electronic modules for signal accommodation, as well as an NI USB – 6218 **acquisition board** manufactured by National Instruments, shown in figure 13.

Fig. 12. General view of the computer system

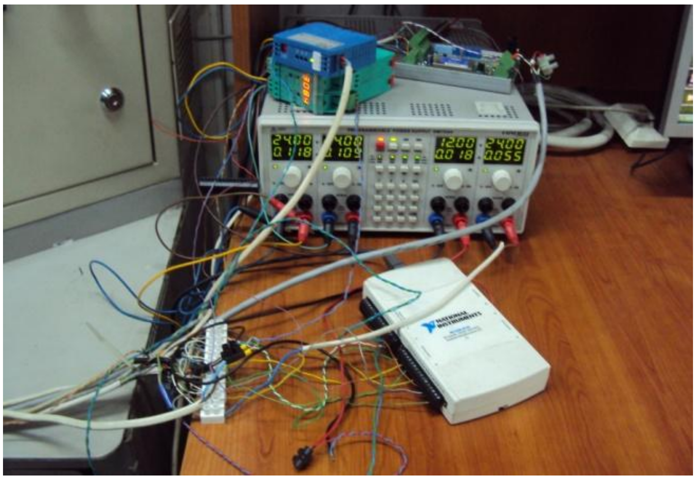


Fig. 13. Supply source and aquisition board

The methodology of conducting the experimental research

In order to determine the pressure losses when the fluid passes through hydraulic directional control valve, the infrastructure presented above has the one being used, and, generally, we proceeded as follows:

- Using the components presented above, we have done their mounting according to the schematic diagram of the stand, shown in fig. 4;
- After the mounting of hydraulic components was completed, there has been done a checking of all hydraulic circuits and sequential tests have been carried out, with manual controls, on operation;
- There have been created all electric and electronic connections imposed by the schematic diagram and by the actual requirements of each individual component, in order to assure electric supply, necessary controls, as well as processing / acquisition of signals from transducers, to store and process them by computer;
- There have been elaborated **special software dedicated to this application**, in the graphical programming environment LabVIEW; its schematic diagram is presented below, in figure 14;
- Determinations, in semiautomatic mode, of pressure loss variation diagrams, depending on the flow that transits the device, have been based on a **proportional electric control** of the PDV device, shown in figure 4, for variation of the pump P displacement, in order to achieve variable flow rate at the pump P, in the working range of the directional control valve. Proportional electrical control, presented in the fig.15, from 0 to 5A, and then from 5 to 0 A, aimed both at continuous increase in the flow up to the maximum value considered as acceptable and at continuous decrease of it, from the maximum value down to the minimum respective value;
- Data regarding variation of interest parameters have been acquired and processed by computer, based on the elaborated software, and presented both in graphical form and as folders of numerical values. Thus, we have achieved variation of pressure losses, in both flow variation directions, and the final diagram resulted revealed the occurrence /existence of **hysteresis**, a phenomenon which is known / present in technical systems.

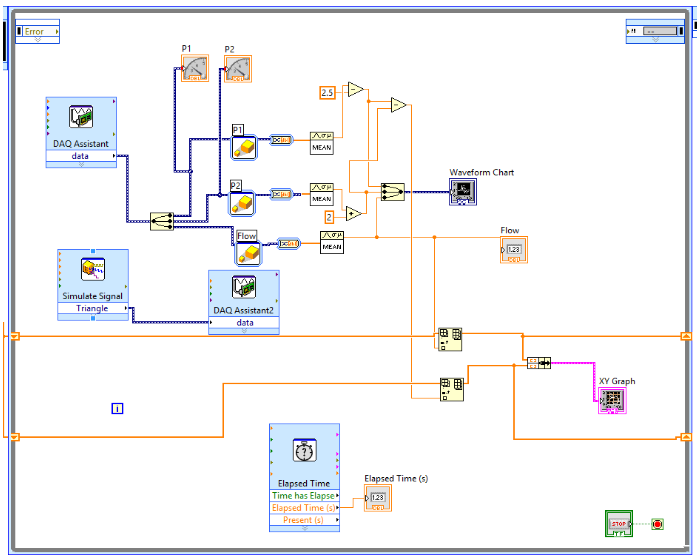


Fig. 14. Logical diagram of the application-dedicated software

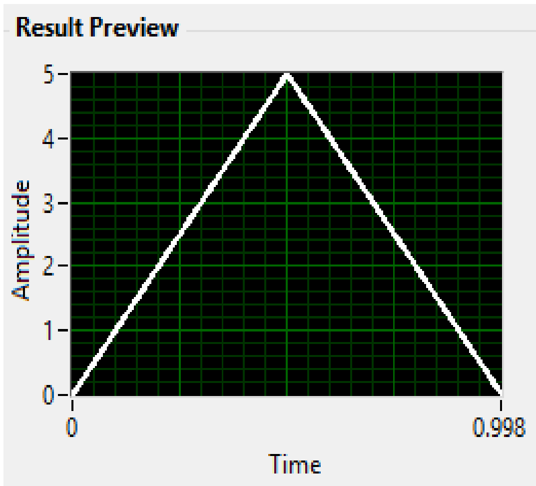


Fig. 15. Proportional control chart of pump flow

The use of testing infrastructure, presented above has resulted in obtaining several sets of extremely interesting experimental results, which allowed plotting the variation curve of pressure losses, when the working fluid passes through the hydraulic directional control valve under tests, depending on the oil flow that transits the device, an example being presented below.

4. Presentation of several experimental results achieved

As a result of conducting the experimental research concerning determination of pressure losses when the working fluid passes through hydraulic directional control valves, we have achieved **a set of complex** data **folders**, registered and processed by computer, which include: a numerical text folder, a folder with plots on the screen, regarding variation of pressure p1, at directional control valve input, variation of pressure p2, at directional control valve output, variation of flow Q, and also **the goal chart of the research**, namely **variation of pressure losses through the directional control valve depending on the** oil **flow variation**, both at increase in flow rates and at decrease in the rates. All these diagrams are obtained automatically on computer, based on the **special software elaborated** for this application. From this set of complex diagrams achieved, figure 16 presents **an example of computer screen** with variations of the interest parameters mentioned above.

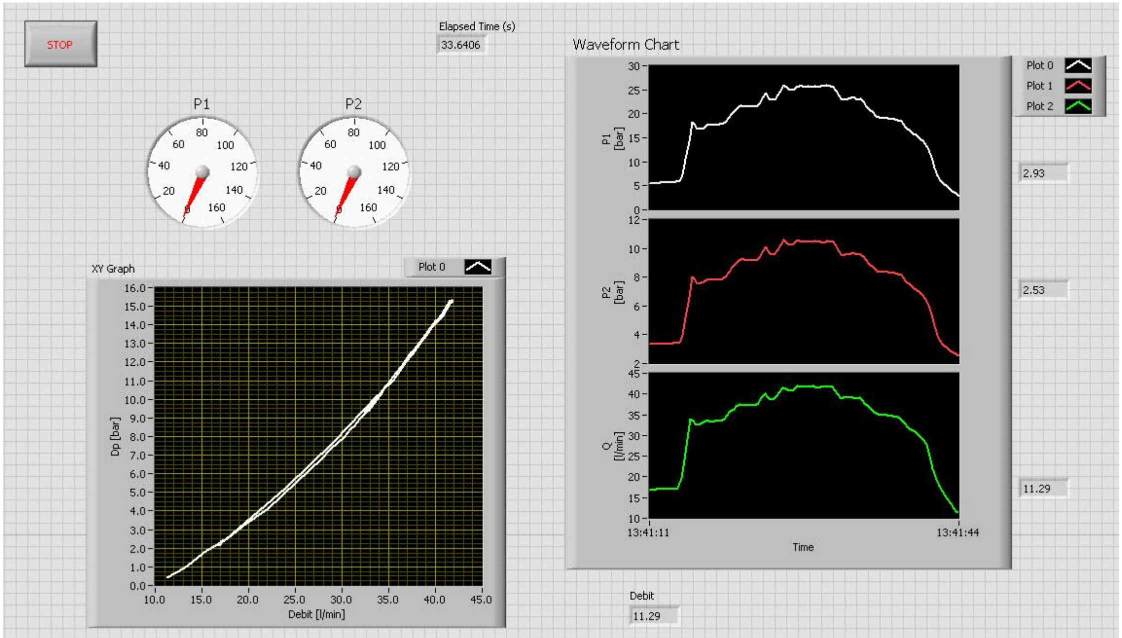


Fig. 16. Pressure and flow graphical variations on the computer screen

For a numerical assessment of pressure loss variation depending on flow variation, from the “txt” numerical folder there have been selected the values shown in table 1, when flow increases, and in table 2, when flow decreases.

Table 1: Variation of pressure losses when flow increases

Q [l/min]	17	19	24	32	34	36	38	40	42
Δp [bar]	2.3	3.2	5.3	9.3	10.2	11.t	13.2	14	15.3

Table 2: Variation of pressure losses when flow decreases

Q [l/min]	40	38	36	34	32	30	28	25	20
Δp [bar]	14.0	13.1	11.0	10.3	9.0	8.0	7.0	5.6	3.3

Figure 14 also shows the existence of **the goal chart of the research**, which presents **variation of pressure losses through the directional control valve depending on the** oil **flow variation**, both at increase in flow rates and at decrease in these rates; this chart after being processed by computer, looks like in fig. 17.

For validation of the results achieved and confirmation of the testing methodology used, figure 18 shows a multiple diagram, obtained / conceived by the company REXROTH BOSCH GROUP.

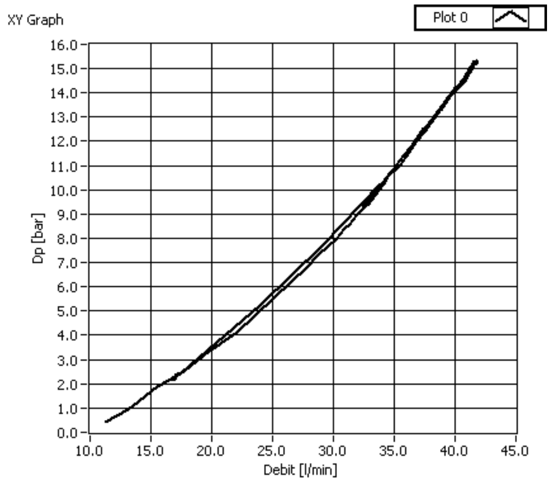


Fig. 17. Variation of pressure losses depending on flow

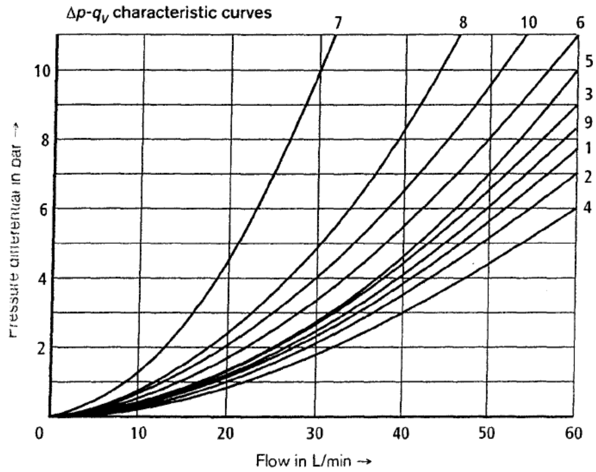


Fig. 18. Variation of pressure losses in literature [6]

From the **comparative analysis** of the diagram obtained in the laboratory experimental research, presented in fig. 17, and the multiple diagram in fig.18, which is elaborated for various schemes of directional control valves, we can conclude that the shape of pressure loss variation is identical, and in terms of value, the resulted graph is placed between graph 7 and graph 8 in the diagram in fig.18.

On the other hand, the experimental research conducted in the institute INOE 2000-IHP reveals existence of a hysteresis between flow increase phase and flow decrease phase, actually an expected phenomenon, and the obtained graph quantifies exactly its value in each point.

5. Conclusions

In the first part of the article, there are presented some general theoretical considerations concerning quantification / assessment, in theoretical mode, of pressure losses when the fluid flow passes through the hydraulic directional control valves used in hydrostatic drive systems.

In the second part of the article, there is presented a laboratory experimental research, concerning determination of the pressure losses when the fluid flow passes through a hydraulic directional control valve with rated diameter of 6 mm, for which there has been designed and developed a complex test stand that includes a computer system for data acquisition, registration and processing, facility that made it possible to obtain of a complex graph, that includes both variations of input and output flow pressure rates and a final graph of variation of pressure losses when the variable flow passes through the directional control valve under testing.

In comparison to the data from literature, we conclude that the shape of the pressure loss variation curve is identical to the known one, and in terms of value the resulted graph is placed in normal domain, corresponding to various schemes of functionality of hydraulic directional control valves of the given size.

The original part of this research is the fact that, based on special software elaborated for this application, in the resulted graph **there also occurs hysteresis** between the flow increase and decrease phases.

Based on the achieved graphical and numerical results, but especially by comparison to the data in the specialized literature, we can conclude that **the methodology used is correct**, it corresponds to the intended purpose and can be extended also to other sizes and dimensional types of hydraulic directional control valves.

Acknowledgement

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