Determining the Times of Charging and Discharging of Hydro-pneumatic Accumulators

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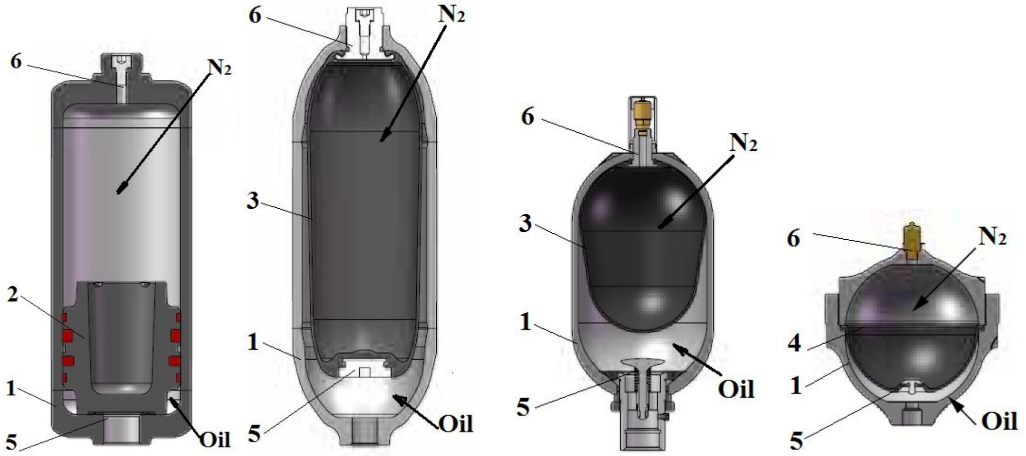
Abstract: *The authors present in this paper some research on the behavior of the hydro-pneumatic accumulators in the hydraulic installations of the machine-tools. They introduce the mathematical models that describe the phases of charging and discharging of these accumulators, taking into account the actual operation of the installation. There are also presented the results of some simulations of installations with accumulators, but also the hydraulic installation with which they checked the mathematical models developed. In this paper, the authors intended to determine the actual time in which the accumulators are able to take over the task of the pumps to supply an oil flow in a certain pressure range. Among the hydraulic installations with accumulators for which the obtained results could be used, we mention: hydrostatic suspension systems of heavy duty vertical lathes, lubrication systems of the bearings that operate on shafts with high inertial masses, hydraulic systems for safety, hydraulic systems that use accumulators as additional source of energy, hydraulic systems for balance etc.*

Keywords: *hydro-pneumatic accumulators, machine-tools, sources of hydraulic energy*

1. Introduction

Accumulators are hydraulic components that enable the reception, storage and transmission of hydrostatic energy under the form of liquid volumes under pressure. The low degree of compressibility of the liquids makes it difficult to store energy in small volumes, but allows the transmission of high efforts. Unlike liquids, gases have great possibilities in terms of compressibility, which allows the storage of a relatively high energy in low volumes. The association of liquids and gases, in special systems has led to the manufacture of hydro-pneumatic accumulators [1].

The currently used hydro-pneumatic accumulators are piston type (a.), bladder type (b.) or diaphragm type (c.). The structure of these accumulators is shown in Figure 1 [1, 2, 3, 4, 5].



a. b. c.

Fig. 1. Hydro-pneumatic accumulators: a.- piston accumulators, b.- bladder accumulators, c.- diaphragm accumulators

Notations in Figure 1 are the following ones: 1 - body of accumulator, 2 - piston, 3 - bladder, 4 - elastic diaphragm, 5 - oil inlet/outlet valve, 6 - nitrogen charging valve (N_2). In accumulator body 1, the oil and nitrogen are separated by means of the piston 2 or bladder 3 or, for smaller volumes, by an elastic diaphragm 4. Initially, the accumulator is charged with nitrogen at a predetermined pressure, by valve 6. If oil pressure is higher than nitrogen pressure, valve 5 opens and the accumulator takes over a certain amount of oil. If the pressure of nitrogen is higher than the pressure in the hydraulic installation, then the oil from the accumulator is sent to the installation (HI).

Keeping the same notations, the accumulators shown in the figure above can be presented schematically as in Figure 2.

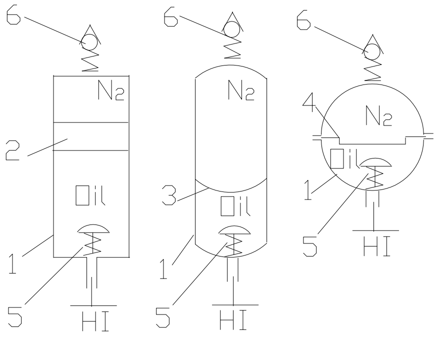


Fig. 2. Schematic representation of hydro-pneumatic accumulators

Elements 2, 3 or 4 separate the nitrogen (N_2) of the upper chamber from the oil of the hydraulic installation (HI). Further, for developing the mathematical models, we shall take into consideration the case of piston accumulators, but the results can be applied to all types of hydro-pneumatic accumulators.

2. Recharging the accumulator with oil

The accumulator defined by its total volume, denoted by V_0, is usually charged with nitrogen through valve 6 of Figures 1 and 2 at pressures p_0. If the installation where the accumulator will be assembled operates between a minimum pressure p_{min} and a maximum pressure p_{Max}, the nitrogen charging pressure checks the relations [1, 5]:

$$p_0 = k \cdot p_{min} \tag{1}$$

$$k \in [0.6 - 0.9] \tag{2}$$

When starting the hydraulic installation, the accumulator will be charged with oil as in Figure 3.

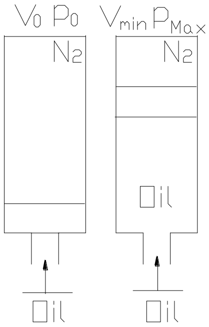


Fig. 3. Recharging the accumulator with oil

If considered that the accumulator circuit is supplied by a constant flow pump having its value Q_P and that nitrogen undergoes an isotherm transformation, it will be obtained:

$$p_0 \cdot V_0 = p_{Max} \cdot V_{min} \tag{3}$$

$$\Delta V = V_0 - V_{min} \tag{4}$$

$$Q_p \cdot t_I = \Delta V \tag{5}$$

$$t_I = \frac{V_0}{Q_P} \cdot \left(1 - \frac{p_0}{p_{Max}}\right) \tag{6}$$

In the relations (3) ÷ (6) it was also noted: V_{min} - minimum volume of nitrogen, ΔV - volume of oil that enters the accumulator, t_I - time of accumulator recharging.

3. Discharging the accumulator during operation

In the phases in which the accumulator is discharged, providing the circuit with oil, as shown in Figure 4, it can be considered that the existing nitrogen undergoes transformations in accordance with:

$$p_{Max} \cdot V_{min}^{\gamma} = p \cdot V^{\gamma} = p_{min} \cdot V_{Max}^{\gamma} \tag{7}$$

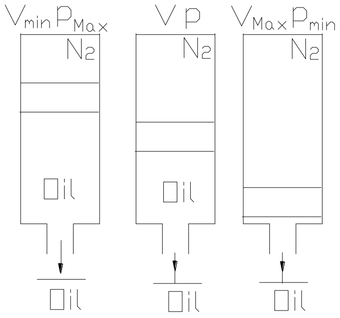


Fig. 4. Discharging of accumulator

In the equation (7) it was noted by γ the index of nitrogen transformation which has the values: $\gamma = 1$ - for the transformations that take place during tens of seconds or even minutes (isothermal) and $\gamma = 1.4$ - for the transformations taking place in matter of seconds (adiabatic).
From the relation (7) it results:

$$V = \frac{p_0 \cdot V_0}{p_{Max}^{1-\frac{1}{\gamma}}} \cdot p^{-\frac{1}{\gamma}} \tag{8}$$

The flow provided by the accumulator has the expression:

$$Q = \frac{dV}{dt} = \frac{dV}{dp} \cdot \frac{dp}{dt} \tag{9}$$

From the relations (8) and (9) it will be obtained:

$$Q = K \cdot p^{-1-\frac{1}{\gamma}} \cdot \frac{dp}{dt} \tag{10}$$

In the relation (10) it was denoted by K a constant specific to the accumulator of volume V_0, which is charged at pressure p_0 and runs at maximum pressure p_{Max}, with value:

$$K = -\frac{p_0 \cdot V_0}{\gamma \cdot p_{Max}^{1-\frac{1}{\gamma}}} \tag{11}$$

It may be considered that this discharge of accumulator is made through a throttle valve, cartridge throttle or a flow control valve towards a circuit where the useful pressure (p_U) is greater than or equal to atmospheric pressure. The condition of proper operation of the installation is that the useful pressure checks any time the relation below:

$$p_{min} \geq p_U \tag{12}$$

It is considered that accumulator discharging is performed by actuating the directional valve DV in Figure 5.

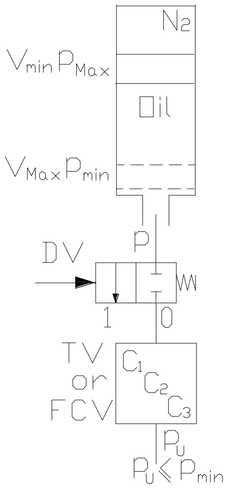


Fig. 5. Discharging of accumulator by throttle valve (TV) or by flow control valve (FCV)

In Figure 5, the constants specific to various modes of discharge (to be defined below) were denoted by C_1, C_2 and C_3.

The flow discharged by various hydraulic resistances depends on the pressure difference between input and output. In these conditions, the following three dependents can be taken into consideration:

$$Q = f_i(p) \tag{13}$$

$$f_1(p) = C_1 \cdot \sqrt{p - p_U} \tag{14}$$

$$f_2(p) = C_2 \cdot (p - p_U) \tag{15}$$

$$f_3(p) = C_3 \tag{16}$$

$$i \in \{1,2,3\} \tag{17}$$

Discharging through a throttle valve is made according to function f_1. Such discharges are found in the hydraulic installations for balance, compensation or hydrostatic [6, 7, 8, 9, 10]. If the discharging is performed through a coil, as in the case of hydrostatic guideways [11, 12], it can be considered that the flow is described by function f_2. If the discharge is made by a flow control valve [1, 11], it shall be considered that the pressure does not influence the value of flow, according to function f_3.

By equaling the expressions (10) and (13), we obtain finally, after integration:

$$K\cdot\int_{p_{Max}}^{p_U}\frac{dp}{p^{1+\frac{1}{\gamma}}\cdot f_i(p)}=\int_0^{t_U}dt=t_U \qquad (18)$$

In the relation (18) we denoted by t_U - the useful discharge time of accumulator, namely the time for useful discharging of accumulator, thus the time when it covers, alone or together with the pump, the necessary of oil.

Relation (18) has general character and it will be used for making specific customizations as follows:

- Υ will be 1 for isothermal transformations (in tens of seconds or even minutes) and 1.4 in the case of adiabatic transformations (matter of seconds).
- p_U - is the pressure of the filled circuit (it may be considered as "0" if the spill is at atmospheric pressure).
- C_1, C_2, C_3 - are the constants whose value is usually given in the catalogues of the manufacturers of hydraulic equipment [4].

For example, when an accumulator is discharged in isothermal mode, towards the hydrostatic pockets of a machine tool, at atmospheric pressure, in case of failure of the pump, it will be obtained [10]:

$$t_U=\frac{2}{3}\cdot\frac{p_0\cdot V_0}{C_1}\left(\frac{1}{p_{min}\cdot\sqrt{p_{min}}}-\frac{1}{p_{Max}\cdot\sqrt{p_{Max}}}\right) \qquad (19)$$

In this case, constant C_1 has the expression:

$$C_1=C_{TV}\cdot S_{TV}\cdot\sqrt{\frac{2}{\rho}} \qquad (20)$$

In the relation (20) it was denoted: C_{TV} - constant of throttle valve (given in catalogue), S_{TV} - surface of throttling, ρ - density of the oil used.

4. Simulation of hydro-pneumatic accumulators operation [13, 14]

The following numerical values have been considered for these simulations: V_0 = 4 l, p_{min} = 100 daN/cm^2, p_{Max} = 200 daN/cm^2, p_0 = 90 daN/cm^2, Q_P = 2.4 l/min.

The accumulator is charged in conformity with the feature in Figure 6.

Charging time in these conditions is t_l = 60 s. If replacements are made in relation (6) we obtain t_l = 55 s.

To simulate accumulator discharging, it is considered that the discharge is made through a throttle valve with openings expressed in percentages related to the maximum opening. Figure 7 shows the evolution of flow and pressure when throttle valve opening is 70%.

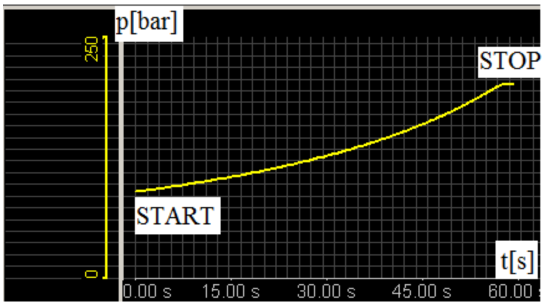


Fig. 6. Charging of accumulator

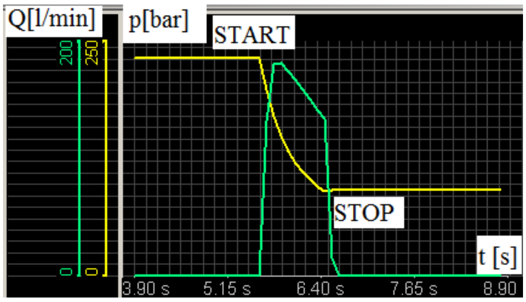


Fig. 7. Features for opening of 70%

Flow reaches values of 150 - 180 l/min for approximately 1 s.

If throttle valve is closed so the surface of throttling becomes 15% of the maximum surface, the

flow is approximately 12 - 15 l/min for about 9 s, according to the feature in Figure 8.
If the throttle valve is closed up to a value of 3% of the maximum value, we shall have the features in Figure 9.

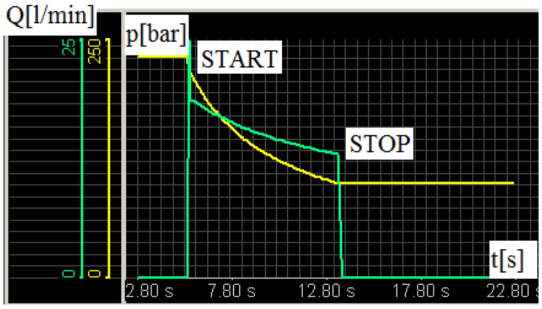


Fig. 8. Features for opening of 15%

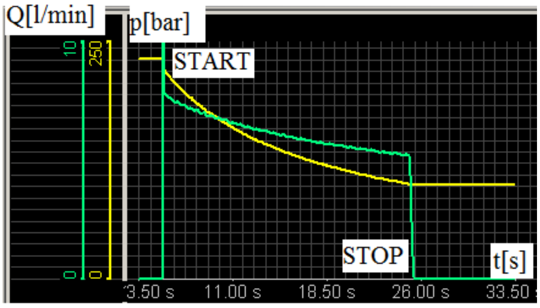


Fig. 9. Features for opening of 3%

In this case, the flow rate is between 8 l/min and 5.5 l/min for approximately 22 s.
If a flow control valve adjusted at the value Q_R = 4 l/min is used instead of the throttle valve, we shall obtain the feature of Figure 10.

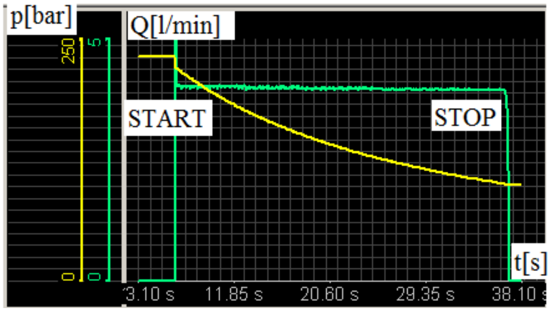


Fig. 10. Discharging of accumulator through a flow control valve adjusted at value Q_R = 4 l/min

In this case, the constant flow rate of 4 l/min is ensured for approximately 29 s.

5. Experimental determination of the times for charging/discharging of hydro-pneumatic accumulators

On the occasion of the remanufacture of a machine-tool, its hydraulic installation has been adapted so to be able to perform the measurement of times, pressures and flow rates. The hydraulic diagram of this installation is shown in Figure 11.
Notations in Figure 11 are as follows: 1 - suction filter (SF), 2 - pump (P), 3 - electric motor (EM), 4, 13 - manometers (1M, 2M), 5 - pressure valve (PV), 6, 16 - directional valves (DV1, DV2), 7 - return filter (RF), 8 - level gauge (IN), 9 - tank (T), 10 - check valve (CV), 11, 12 - pressure switches (PS1, PS2), 14 - safety block (SB), 15 - accumulator (Ac), 16 - pressure transducer (PT), 17 - throttle valve (TV), 18 - flow control valve (FCV), 19 - flowmeter (FI).
Pump P driven by the electric motor EM sucks oil via suction filter SF from the tank T. The working pressure of the pump is viewed on manometer M1. The value of this pressure is adjusted using the pressure valve PV. By actuating the electromagnet 1S of the directional valve DV1, the oil will be sent to the accumulator Ac via the check valve CV. The pressure in the circuit of accumulator is read by means of manometer M2 and pressure transducer PT. The accumulator is equipped with the safety block SB [4]. The pressure switches are adjusted as follows:

- PS1 is adjusted at minimum pressure (p_{min}) and controls the charging of accumulator circuit (1S+) and the uncoupling of the associated circuit (3S+,2S-).
- PS2 is adjusted at maximum pressure (p_{Max}) and controls the uncoupling of charging (1S-) and the coupling of the associated circuit (2S+,3S-).

By actuating the directional valve DV2 (2S+), the oil from the accumulator is sent to the throttle valve (TV) or to the flow control valve (FCV). The flow is measured by means of the flowmeter (FI). In Figure 11 it was also noted: NI - level gauge, TV - throttle valve, FCV - flow control valve.

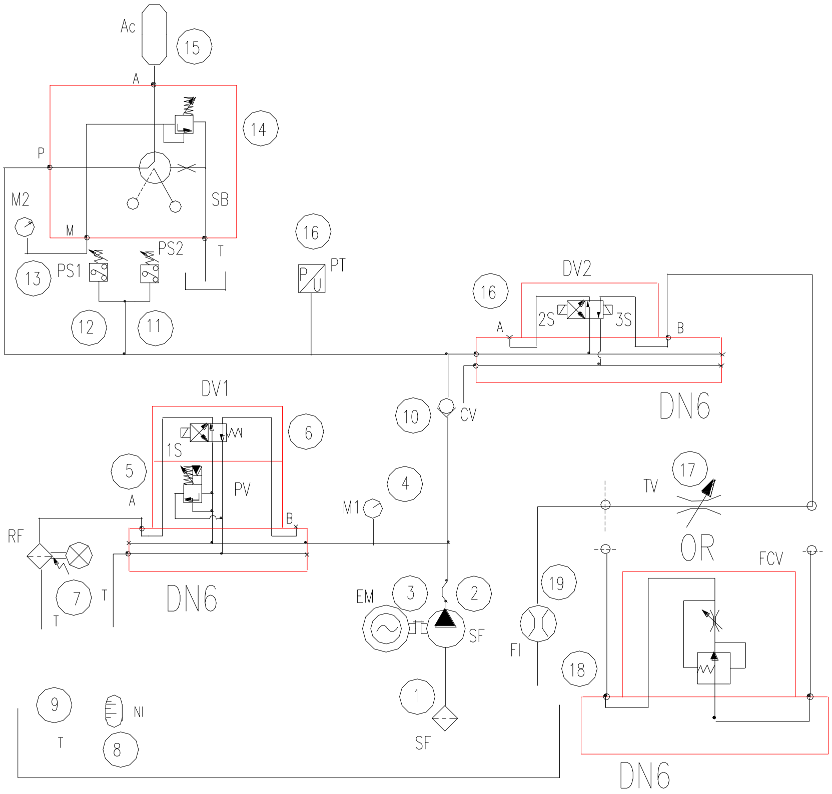


Fig. 11. Hydraulic diagram of the installation

The measured flow rates are average values. They were obtained by measuring the volume spilled over and the associated times.

For comparison, the results obtained by calculation, simulation and experiments are shown in Table 1.

Table 1: Time for charging and discharging the accumulator

	Analytical calculation	**Simulation**	**Measurements**
Charging time [s]	55	60	64
Time for discharging by open throttle valve 15% [s]	11 Flow 13.6 l/min	~9 Flow ranging from 12 to 15 l/min	~7 Average flow ~13 l/min
Time for discharging by flow control valve adjusted at 4 l/min [s]	27	~29	~26

6. Conclusions

The use of hydro-pneumatic accumulators in the hydraulic installations is more and more frequent. Among the advantages of using the hydro-pneumatic accumulators we can mention:

- diminution of the pumps flow;
- storage of hydraulic energy during the phases when the installations have low consumption;
- ensuring uninterrupted operation of the installations for a certain period, even in the event of pump stop.

Accumulators are usually charged in a longer period than the period necessary for discharging. To determine the time of discharge but also the flow rate usable in a certain range of pressures, in this paper were developed mathematical models that can be used in most hydraulic installations of different fields. According to the type of installation, one can use the mathematical model that corresponds to the discharge:

- flow depending on pressure drop;
- flow depending on the root of the pressure drop;
- flow that is not dependent on pressure drop if flow control valves are used.

In order to benefit from the mathematical models presented in the paper, one shall use the features specific to the equipment utilized, in conformity with catalogues of the manufacturers.

Specialized simulation programs can be used successfully provided that the features of the actual equipment are known.

The experimental measurements confirm the accuracy of the mathematical models developed.

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