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Influence of Temperature Variations on the Operating Characteristics of the Hydro-Pneumatic Accumulators

Prof. PhD Eng. **Anca BUCUREȘTEANU**[1,*]

[1] University POLITEHNICA of Bucharest
* ancabucuresteanu@gmail.com

Abstract: *In this paper, the authors present the mathematical models that can be used to determine the correlation between the variations of temperature and pressure in the industrial hydraulic units equipped with hydro-pneumatic accumulators. Two real cases of utilization of these systems are shown. First of all, the hydraulic units in which the oil volume in the accumulator circuit is negligible (as in the case of machine-tools and constructions equipment) are presented. The second case is the one of the units where the oil volume in the accumulator circuit is much higher than the accumulator volume, as in the case of the heavy-duty hydraulic presses, for example.*

Keywords: *Hydro-pneumatic accumulators, heating of hydraulic units, mathematical models*

1. Introduction

Accumulators are hydraulic components that allow the reception, storage and transmission of the hydrostatic energy in the form of volumes of oil under pressure [1, 2, 3].
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 enable them to store large energies in small volumes. The association of liquids and gases within special constructions led to the making of hydro-pneumatic accumulators.
Diaphragm or bladder accumulators achieve a perfect gas - liquid separation.
For small volumes of liquid (less than 10 l), the separation is made by a flexible rubber diaphragm placed between the two chambers of the accumulator as in Figure 1.

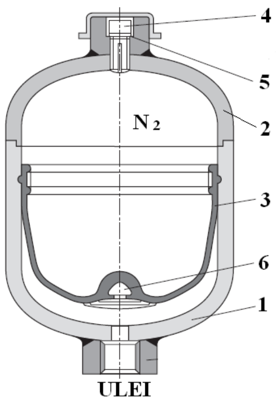


Fig. 1. Hydro-pneumatic accumulator with diaphragm

The following denotations were used in the figure above: 1 and 2 represent two parts that determine (by welding) the total volume of the accumulator; 3 – diaphragm; 4 and 5 - elements through which the nitrogen loading is performed. To prevent extrusion at total emptying, there is a metal part 6 in the center of the diaphragm.
The material of the diaphragm must meet specific requirements, like: to be resistant to oil and gas, to be less sensitive to wear and tear, less sensitive to fatigue, to have good elasticity.
The advantages of using this type of accumulator are the following ones: there are no frictional forces; the sealing is perfect; it is possible to operate at pressure of 500 - 600 daN/cm^2.

Disadvantages include: firstly, the reduced capacity and secondly the fact that the elastomer cannot be used at temperatures below 25 ^{0}C.
If a bladder made of the same material is used instead of the diaphragm, the volume of the accumulator increases a lot, reaching volumes larger than 50 l. Such an accumulator is shown in Figure 2 and is formed of: 1 - one-piece body; 2 - bladder; 3 – nitrogen charging valve; 4 - shut-off valve.

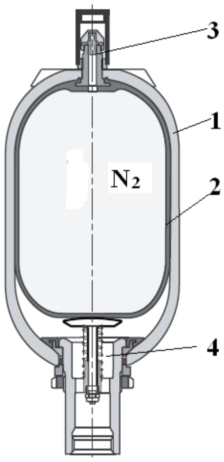


Fig. 2. Hydro-pneumatic accumulator with bladder

The liquid passes from the accumulator to the hydraulic unit and inversely through the holes under the valve 4. In the case of a complete discharge of the accumulator, the valve 4 protects against the extrusion of the bladder and does not allow the clogging of the accumulator inside part.
The installation of the accumulator (or accumulators in parallel) is usually done according to the diagram in Figure 3.

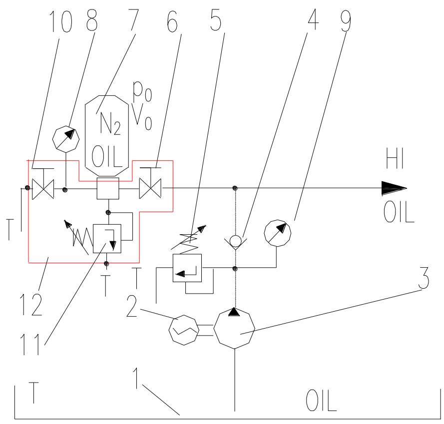


Fig. 3. Installing the accumulator

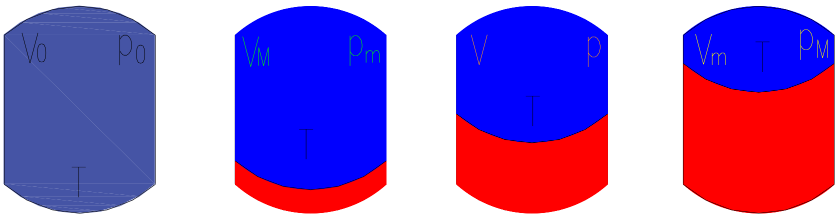
Pump 3, driven by the electric motor 2, sucks the oil from the tank 1 (T). The oil is sent to the hydraulic unit IH but also to the accumulator 7 via the check valve 4. This valve does not allow the accumulator to be discharged through the pump. The maximum pressure in the unit is adjusted by means of the pressure valve 5. The oil enters the accumulator through the valve 6. The supply pressure (at the pump) is displayed on the manometer 9, while the pressure in the accumulator is displayed on the manometer 8. For the discharge of the accumulator, the valve 10 should be opened. As shown below, it is preferable to have also a safety valve 11, set at a pressure value higher than the pressure of the valve 5. In most cases, the elements 6, 8, 10 and 11 are mounted on a block 12, called a safety block.

Accumulator 7 has the volume V_0 and is charged with nitrogen at the pressure p_0, this one depending on its role in the unit [2, 3]. If the unit operates at a pressure ranging from the minimum value (p_m) and the maximum value (p_M), then the volume of nitrogen will evolve accordingly between the maximum value (V_M) and the minimum value (V_m). Under these limitations, at any moment, if the ambient temperature t does not change, the nitrogen has volume V and pressure p so that the conditions are met:

$$p_0 V_0 = p_M V_m \tag{1}$$

$$p_M V_m^n = p V^n = p_m V_M^n \tag{2}$$

Relation (1) represents the first charge of the accumulator in the circuit, considered as isothermal.
Relations (2) describe the transformations of nitrogen between its states. In the case of nitrogen, the polytropic coefficient n changes between the values 1 at the isothermal transformation and 1.4 at the adiabatic transformation [3, 4].
The transformations undergone by nitrogen, in conformity with the relations above, were represented in Figure 4.



a. b. c. d.

Fig. 4. Nitrogen state transformations

Initially,according to Figure 4a, the nitrogen at pressure p_0 takes the entire available volume V_0. When the minimum pressure p_m is reached, the occupied volume is the maximum one V_M, as in Figure 4b. At any time during operation, the nitrogen is characterized by pressure p and fills the volume V, according to Figure 4c. When the maximum value of the pressure p_M is reached, as in Figure 4d, the volume of nitrogen has the minimum value V_m.

2. Heating of the Hydraulic Units – the Cause of the Pressure Increasein the Units Equipped with Hydro-pneumatic Accumulators

2.1 Hydraulic Units with a Negligible Volume of Oil in the Accumulator Circuit

A unit with accumulator that supplies small consumers (cylinders) through pipes of negligible volume is taken into consideration. In the case of a unit for tool clamping/unclamping or saddle locking/unlocking, if the accumulator is in the state shown in Figure 4c, the pressure increases after a while (as indicated by the manometer of the accumulator) because of the heating, even if the pressure at the pump is zero, such as in the case of the pre-control systems [3, 5].
For the gas in the accumulator, if the expansionsof the accumulator, pipes and oil are neglected, it can be considered:

$$\frac{pV}{T} = \frac{(p+\Delta p)(V+\Delta V)}{T+\Delta T} \tag{3}$$

In the relation (3) it was denoted: ΔV - variation of the gas volume; ΔT - increase of temperature and Δp - increase of pressure.
From the relation (3) it is obtained:

$$\Delta p = p\left(\frac{\Delta T}{T} - \frac{\Delta V}{V}\right) \tag{4}$$

When the oil is considered incompressible ($E_{Oil} \rightarrow \infty$, where E_{Oil} represents the modulus of elasticity of oil), for the gas it can be considered that this one undergoes an isochoric transformation, reaching the state shown infigure 5.

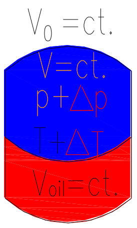


Fig. 5. Isochoric transformation due to temperature increase if oil compressibility is neglected

In this case, the pressure increase Δp will be:

$$\Delta p = p\frac{\Delta T}{T} \tag{5}$$

If the oil compressibility is taken into account, the gas no longer undergoes a constant volume transformation, increasing its volume by the quantity ΔV equal to the compression of oil, as shown in Figure 6.

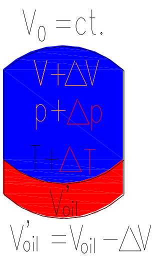


Fig. 6. Gas transformation due to temperature increase if oil compressibility is not neglected

In this case, from the relations above it is obtained:

$$\Delta p = \frac{p}{1+\frac{p(V_0-V)}{E_{Oil}V}}\frac{\Delta T}{T} \tag{6}$$

To see the influence of oil compressibility on the variation of pressure, the following example was taken into consideration: V_0 = 10 l, p_0 = 90 bar, p_M = 200 bar, p_m = 100 bar, T_0 = 293 K (20^{0}C), increase of temperature ΔT = 40 ^{0}C. The heating started when p = p_M, the circuit is without losses and the modulus of elasticity of the oil is E_{Oil} = 1.5 x 10^4 daN/cm^2. If the compressibility is not taken into consideration, Δp = 27.3 bar is obtained. By compressing the oil, the nitrogen occupies a larger volume, in which case the over pressure Δp = 26.86 bar. Therefore, there is a difference of ~0.5 bar or ~2%, which can be neglected, because it is an error that does not impede operation in most cases; moreover, it is even imperceptible on the usual manometers.

If it is considered that Δp ~ 25 bar at a reference pressure of 200 bar, an increase of over 10% can be noticed, which is not negligible at all.

In general, in the case of machine-tools, the equipment used for such units operates at pressures of 300 bar at the most.

Under these conditions and taking into account the relations above mentioned, the characteristic of the over pressure Δp can be drawn as a function of the temperature increase ΔT like in Figure 7.

The reference temperature is t = 20 ^{o}C (293 K) and there are not allowedoil temperatures higher than t_{Max} = 60 ^{o}C (333K), which means a maximum heating of Δt = 40 ^{o}C.

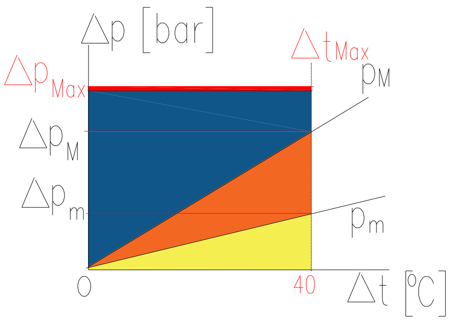


Fig. 7. Characteristic of the over pressure Δp

Another condition imposed in Figure 7 is the one regarding the working pressures: the maximum working pressure p_M added to the pressure increase Δp must not exceed the maximum pressure allowed by the equipment, p_{Max}, which means:

$$\Delta p_{Max} \leq p_{Max} - p_M \quad (7)$$

The heating of the unit occurs with the accumulator at a pressure p which validates:

$$p_m \leq p \leq p_M \quad (8)$$

Under these conditions, according to the characteristic in Figure 7, it results:

$$\Delta p \in [\Delta p_m, \Delta p_M] \quad (9)$$

If the pressure increase Δp is higher than Δp_{Max} there is the risk of destruction of some components because the pressure valve 5 in Figure 3 does not affect the circuit of the accumulator which heats up and is isolated by the check valve 4. The safety block 12 was provided to protect the circuit. This block includes the pressure valve 11 which is set to the necessary value that is higher than the one set at the pressure valve 5. Figure 8 shows a safety block in which the accumulator is coupled/uncoupled manually.

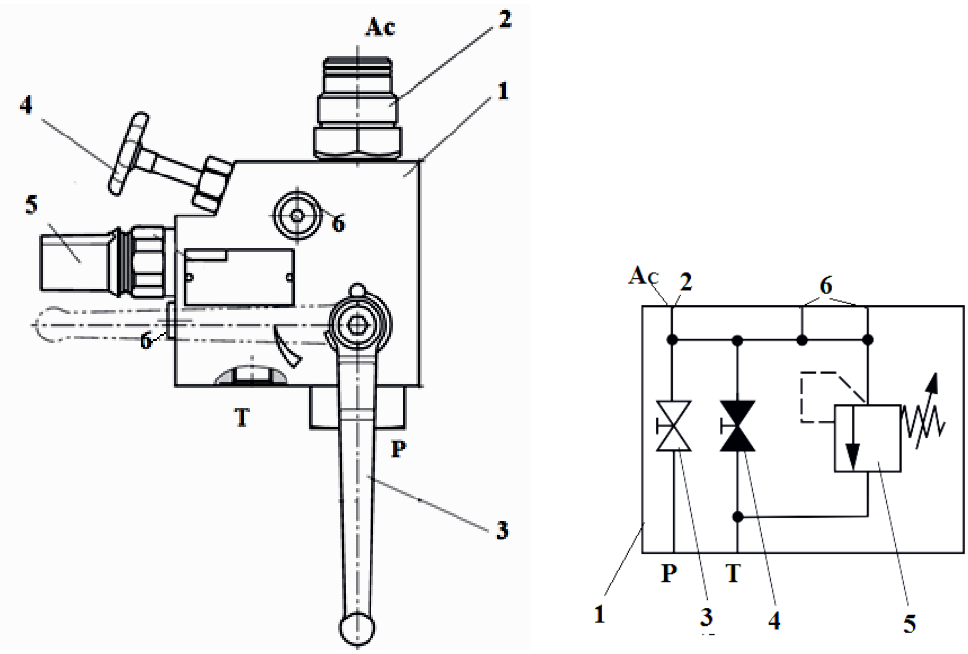


Fig. 8. Manually operated safety block

The fitting 2 for the accumulator Ac is fixed in body 1. The lever 3 makes the coupling and uncoupling of the accumulator to the source (P). Valve 4 discharges the accumulator directly to the tank (T). The intended pressure is set at pressure valve 5. Pressure value can be read on a manometer connected to any of the fittings 6.
The safety block eliminates the risks resulted from the pressure increase caused by the heating. A simulation of the running of a system with and without safety block was used to show how the safety block operates [6, 7]. The results of the simulation are presented in Figure 9.

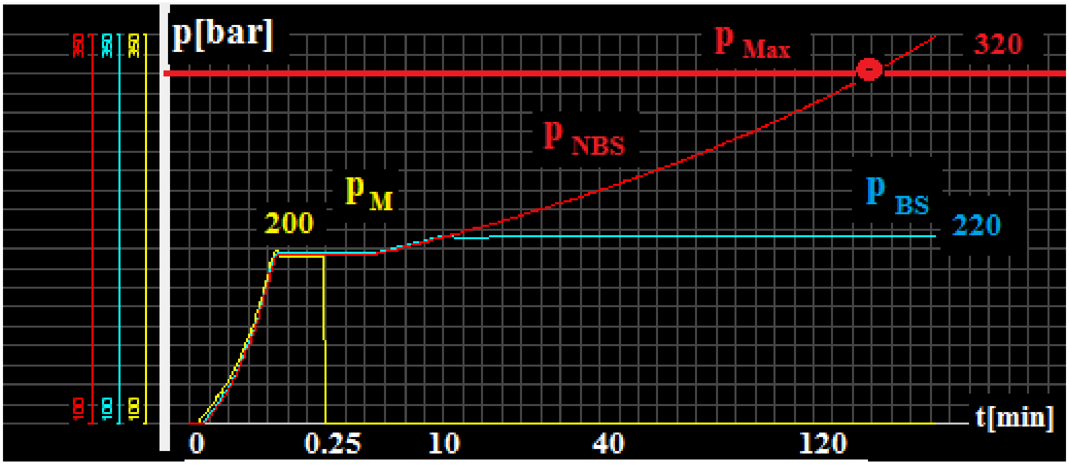


Fig. 9. Simulation of the operation of a system with and without safety block

It was considered that a constant flow pump supplies alternatively two circuits with accumulator at the maximum pressure p_M = 200 bar. The circuits are equipped with pre-control systems [1, 3, 8] which discharge the pump to the tank when maximum pressure is reached. One circuit is provided with safety block adjusted to the safety pressure p_{BS} = 220 bar. The second circuitis not equipped with safety block and the pressure p_{NBS} develops in the accumulator. The maximum pressure allowed by the componentsis p_{Max} = 320 bar. In the case of the circuit provided with safety block, the valve ensures the discharge when the pressure value p_{BS} = 220 bar is reached after approximately 10 minutes of operation, but in the circuit without block it is noticed that after about 150 minutes the risk of unit destruction occurs.

2.2 Hydraulic Units with Large Volume of Oil in the Circuit of the Accumulator

This time, a unit with accumulator that supplies big consumers (cylinders) through large DN pipes is taken into consideration. For example, a unit from a heavy press. In this case, if the accumulator is in the state shown in Figure 10a, after a while it is observed that the pressure increases at the manometer of the accumulator due to heating, even if the manometer of the pumps hows that the pressure is zero; because of the heating, it will be reached the state in Figure 10b.

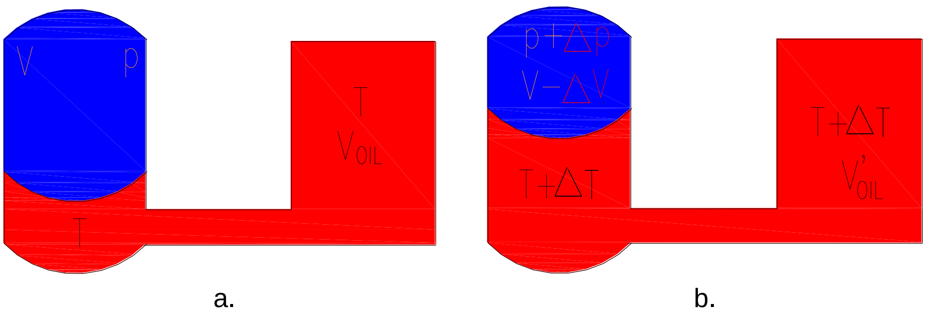


Fig. 10. Increase of the pressure due to oil heating in a circuit with accumulator

By heating, the large amount of oil expands and reduces the volume of nitrogen in the accumulator, increasing its pressure. It is considered that the oil is incompressible and its expansion is done by compressing the gas [3, 8]. The expansion of the accumulator is neglected. Consider the initial volume of oil V_{Oil} at temperature T. After its heating, the volume becomes V'_{Oil}. In these conditions, the following relations are found out:

$$\frac{pV}{T} = \frac{(p+\Delta p)(V-\Delta V)}{T+\Delta T} \tag{10}$$

$$\Delta p = p\left(\frac{\Delta T}{T} + \frac{\Delta V}{V}\right) \tag{11}$$

$$\Delta V = V_{Oil}^{'} - V_{Oil} \tag{12}$$

$$V_{Oil}^{'} = V_{Oil}(1 + \gamma_{Oil}\Delta T) \tag{13}$$

In the above relation, γ_{Oil} denotes the coefficient of volume expansion of the oil (γ_{Oil} = 0.00065 K^{-1}). Finally, the value of overpressure is obtained as:

$$\Delta p = p\frac{\Delta T}{T}\left(1 + \frac{V_{Oil}T\gamma_{Oil}}{V}\right) \tag{14}$$

Relation (14) can be approximated with the expression:

$$\Delta p = p\frac{\Delta T}{T}\left(1 + p\frac{V_{Oil}T\gamma_{Oil}}{V_0 p_0}\right) \tag{15}$$

In this case, the pressure increase has, in addition to the component given by the heating of the nitrogen, another term proportional to the volume of heated oil. Thus, for a volume of oil V_{oil} + 20 l heated with Δt = 40 ^oC, starting from the maximum pressure p_M = 200 bar, a final pressure higher than 250 bar is reached. The pressure increase can influence the value of the charging/discharging times of the accumulators [9].

3. Conclusions

The hydro-pneumatic accumulators are used in most hydraulic units of machine-tools: counter balance units, locking/unlocking systems, clamping/unclamping systems and even the hydrostatic lubrication systems. In most cases, the accumulator sizing or checking calculation is made considering the ambient temperature as constant and, in this situation, the gas undergoes isothermal or adiabatic transformations. In reality, the temperature of the hydraulic environment and also the temperature of the unit is not constant. During operation, the temperature rises, so that in some cases it is even necessary to provide cooling systems. Usually, for machine-tools the reference temperature of the environment is 20 ^0C, while the maximum temperature allowed in the hydraulic units does not exceed 60 ^0C. Therefore, theoretically, the heating by 40 ^0C is possible. This heating affects the gas state transformations in the accumulator, but can also entail large variations in the volume of oil. All this can lead to significant increases of the pressure in the unit that can exceed the value set at the pressure valve, causing the destruction of the unit. In these conditions, it is recommended (in addition to the usual calculations) to check also the overpressure that appears because of the heating. The usual accumulators work at 320 bar at the most, but there are also special accumulators that can operate up to 700 bar.
To protect the systems with accumulators, it is appropriate to use safety blocks manufactured by specialized companies. The pressure valves in these safety blocks must be set at values that do not endanger the unit. These values will be higher than the pressures developed during operation. It is recommended to limit the access to these valves and even to seal them.
The use of the simulation programs for checking the operation of the unit in the design stage is very helpful.

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