THEORETICAL ANALYSIS OF INFLUENTIAL PARAMETERS TO COMPRESSION AND DECOMPRESSION PROCESS OF COMPRESSED OIL IN HYDRAULIC SYSTEMS OF THE PRESS

MILUTIN ŽIVKOVIĆ [1*]

[1]*High Technical Mechanical School Trstenik, Serbia*

Abstract: Compressibility of hydraulic oil is very significant for large diameter cylinder presses, especially if they are exposed to high pressures. The paper presents a theoretical analysis of the process of compression and decompression of oil in the cylinders with and without the presence of air presenting an analog model. Although considerations are relating to the ideal conditions of the process of compaction, the paper defines the basic mathematical processes depending on compression and discharge of the same. They refer to the definition of the time discharge and elimination of adverse effects in the same.

Keywords: compressibility, elasticity modulus, compressive modulus, discharge/

1. INTRODUCTION

Discharge the working chambers of the cylinder, exposed to pressure and is followed by the rapidly expanding elastically deformed mass of oil. If this process, with the cylinder of large diameter and high-pressure pressing, takes place unchecked, it leads to hydraulic shock and oscillatory movement of the cylinder’s piston with a supporting tool, which is accompanied by strikes.

In order to avoid these undesirable effects the excess of compressed oil must take controlled using the appropriate nozzle diameter. Those ones, therefore, must be selected to provide an optimal conducting process: if the diameter of the nozzle was too small then the time of the removal of excess fluid would be too long (which would increase the duration of the technological cycle), and if the diameter of the nozzle was too big then cannot be avoided, the above mentioned harmful effects of process of the decompression hydraulic oil.

To solve these problems in the scientific literature has little practical information while solving of this problem and nozzle selection is performed relying on experience. By choosing different diameter of nozzles defines the most optimal solution related to discharge of the compression volume. In order to analytically describe the process of decompression of hydraulic oil in the hydraulic cylinders of the process it is necessary to previously study the elastic properties of working fluids and the factors affecting its characteristics.

The characteristics of the working fluid expressed by compressibility modulus, literature data and our own experience shows that there are a significant influence on the dynamic characteristics of the system and reliable operation of hydraulic components. It is especially evident in the working fluid exposed to high pressures [1, 2]. If we take into account, inevitably, the presence of air in the working fluid, then problems may arise in their work.

* Corresponding author, email: milutinzivkovicts@gmail.com

The impact is significant if the cylinders of presses are of large diameter and pressures up to 400 bar. If the technological procedure requires the retention of the piston cylinder presses for a long time in a certain position at the maximum pressure, there occurs a significant problem of compression and decompression of the oil.

The paper analyzes the influence of compressibility modulus (via compression modulus) and the manner of its determining through secant and tangent modulus of the fluid (isentropic and isothermal) and the impact of air in the working fluid.

2. IMPORTANCE OF COMPRESSIBILITY MODULUS ON HYDRAULIC FLUIDS

All fluids are compressible, which means that changes in the pressure the working fluid changes its volume. Failure to comply with this fact makes sense only in operation of devices at low values of pressure. At higher pressures and higher volume quantity of the working fluid must be taken into account that, due to compression, it must invest more energy for its compaction. Neglect can have a negative influence on the dynamic characteristics of the hydraulic system and positioning accuracy.

Typical dependence of volume change of hydraulic fluid (V) exposed to the pressure depends on: the initial volume compression (V_0), pressure (p) and the compressibility modulus of the working fluid K [Pa], expression (1) [3].

$$V = f\,(p, Vo, K) \tag{1}$$

When it comes to gases, small pressure differences are caused by small changes in density, so for example, the pressure change by 1% at a constant temperature is resulting in density variation of 1% [4]. The ratio of volume change ΔV and initial volume V is divided by the pressure differential Δp (due to and the volume is changed), has a constant value and is called the coefficient of compressibility (s), (2):

$$s = -\frac{\Delta V}{V} \cdot \frac{1}{\Delta p}\ [Pa^{-1}] \tag{2}$$

where: $\Delta V = V_0 - V$ [m^3] and $\Delta p = p_0 - p_1$[Pa];V_0, p_o–initial volume (pressure) [m^3],[Pa].
or in the form of differential changes:

$$s = -\frac{dV}{V} \cdot \frac{1}{dp} \tag{3}$$

The reciprocal value of the coefficient of compressibility is referred to as the modulus of elasticity (E), which is analogous to the modulus of elasticity (E) of the solids:

$$\mathrm{E} = \frac{1}{\varepsilon} = -\frac{\mathrm{V}}{\mathrm{dV}} \cdot \mathrm{dp}\ [\mathrm{Pa}] \tag{4}$$

The reciprocal value of the compressibility of oil, in literature, is called Bulk's fluid modulus, [5], by equality (5):

Bulk's modulus

$$(K) = -\frac{V_0 \cdot \Delta p}{\Delta V} \tag{5}$$

Since the ratio $V_0/\Delta V$ is dimensionless unit, the unit for the modulus is the same as the pressure drop: Pa, N/m^2 or bar. High value of the Bulk modulus is synonymous with low compressibility, volume changes are relatively small and the fluid is stiffer in use. The Bulk modulus can be expressed as a secant and tangent value in isothermal or isentropic conditions.

Secant bulk modulus: Isothermal secant Bulk modulus is the reciprocal value of the compressibility calculated in conditions where the temperature is constant, Figure 1, equation 6 [6]:

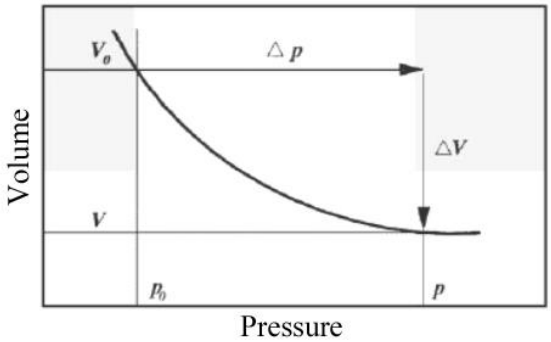

Fig. 1. Secant Bulk modulus.

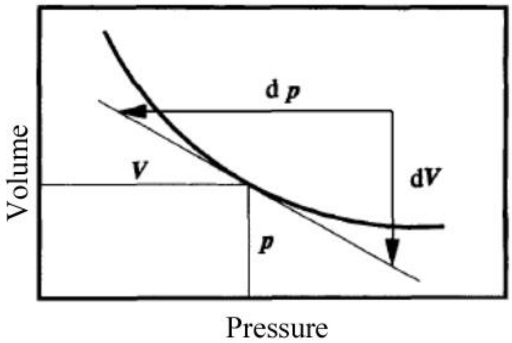

Fig. 2. Tangent Bulk modulus.

$$K_{sec} = -\frac{V_0}{\Delta V} \cdot \Delta p \quad (t = const) \tag{6}$$

and gives an approximate value based on the total decrease in volume over a certain pressure changes. This value can be calculated for any specific fluid from its density or viscosity at atmospheric pressure, expressions (7) and (8) [7]:

$$K_{sec} = (1{,}3 + 0{,}15 \cdot \log \nu) \cdot e^{0{,}0023 \cdot (20 - t)} \cdot 10^4 + 5{,}6 \cdot p \;\; [bar] \tag{7}$$

$$K_{sec} = [1{,}51 + 7 \cdot (\rho - 0{,}86)] \cdot e^{0{,}0023 \cdot (20 - t)} \cdot 10^4 + 5{,}6 \cdot p \;\; [bar] \tag{8}$$

Where: p – pressure in bar; t – temperature in °C; ν – kinematic viscosity at atmospheric pressure in cSt; ρ – density at 20°C and atmospheric pressure in kg/m^3.

Isentropic (dynamic) Bulk secant modulus is desired parameter when sudden changes in pressure and temperature of the fluid must be taken into account. Typical examples are the calculation of the size of the force acting on the system components and the speed of reaction of servomechanism, by equality (9) [8]:

$$K_{sec} = -\frac{V_0}{\Delta V} \cdot \Delta p \quad (at\ constant\ entropy) \tag{9}$$

As with isothermal and isentropic Bulk secant modulus can be calculated using the density of kinematic viscosity of a fluid, or at atmospheric pressure, the expressions (10) and (11) [9]:

$$K_{sec} = \{1{,}57 + 0{,}15 \cdot \log \nu\} \cdot e^{0{,}0024 \cdot (20 - t)} \cdot 10^4 + 5{,}6 \cdot p \;\; [bar] \tag{10}$$

$$K_{sec} = [1{,}78 + 7 \cdot (\rho - 0{,}86)] \cdot e^{0{,}0024 \cdot (20 - t)} \cdot 10^4 + 5{,}6 \cdot p \;\; [bar] \tag{11}$$

Tangential Bulk modulus, Figure 2: Isothermal tangential Bulk modulus scientifically defined the exact value at a constant temperature. As the name itself suggests, the tangent modulus is derived from the gradient of the curve volume-pressure and is specific for the pressure p at which the measured gradient - dV/dp, [9], equation (12):

$$K_{tan} = -V \cdot \left(\frac{dp}{dV}\right) \; (t = const\,) \tag{12}$$

The corresponding isentropic Bulk tangent modulus can be calculated by multiplying the isothermal modulus value c_p/c_v, respectively with the relationship of the specific heat of the fluid at constant pressure and volume.

Typical value of the ratio c_p/c_v for mineral oils are given in the Table 1 [5]:

Typical values of surface isentropic Bulk modulus for mineral oils at a temperature of 50°C and at atmospheric pressure are $1.62 \cdot 10^3$ MPa (ISO VG100) and $1.57 \cdot 10^3$ MPa (ISO VG32) [10]. Bulk modulus decreases with temperature, but increases with the pressure (Figure 3) [11]. Sudden expansion of compressed working fluid (oil), from which comes the discharge of the working chamber in the cylinder, significantly affects the dynamic behavior of the working elements of machines.

Table 1. Typical value of the ratio c_p/c_v for mineral oils

Temperature [°C]	**c_p/c_v**	
	Atmospheric pressure	**70 [MPa]**
10	1.175	1.15
60	1.166	1.14
120	1.155	1.13

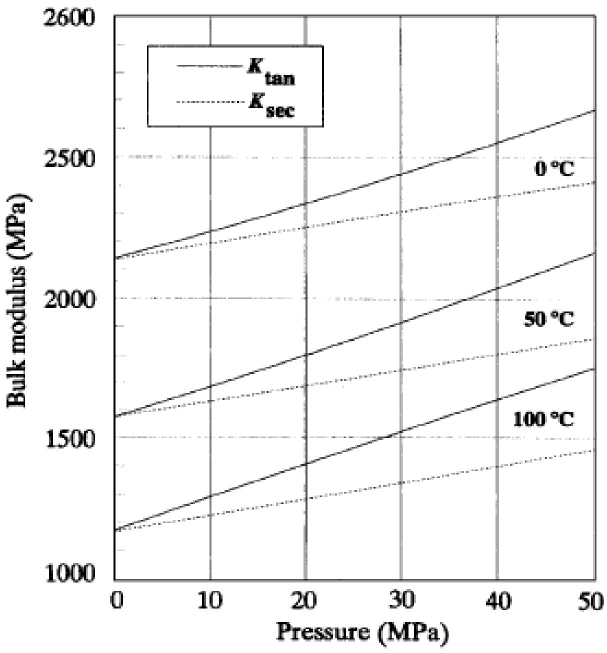

Fig. 3. Isentropic Bulk modulus for mineral oil ISO VG32.

3. ELASTICITY MODULUS OF PURE OIL AND MIXTURE OF HYDRAULIC OIL AND AIR

For the analysis of the behavior of elasticity of the working environment can be used analog mechanical model, Figure 4 [12]. The model is analogous to the behavior of solids, i.e., so and here will be introduced the coefficient of elasticity of the environment (C), using the expression (4) is obtained an expression (13);

$$C = -\frac{\mathrm{dF}}{\mathrm{dh}} = -\frac{A \cdot \Delta p}{dh} = \frac{A \cdot \frac{dV}{V} \cdot K}{dh} = \frac{K \cdot A}{h} = \frac{K \cdot F}{h \cdot p} \tag{13}$$

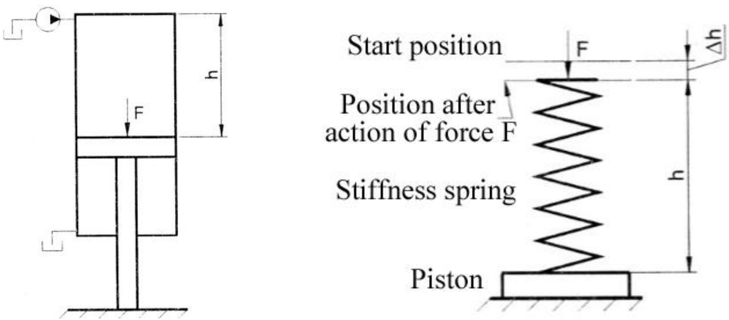

Fig. 4. Hydraulic cylinder exposed to pressure of the hydraulic fluid and the corresponding mechanical model.

The negative sign shows that the increase in force leads to compaction (decrease) of volume exposed to compaction. Neglecting the change of volume elasticity modulus environment (K), the coefficient of elasticity (C) is a constant which leads to deformation of the "oil" spring, expression (14) [13].

$$\Delta h = \frac{F}{C} = \frac{p \cdot A}{\frac{K \cdot p \cdot A}{h \cdot p}} = \frac{h \cdot p}{K} \qquad (14)$$

However, a change in the elastic properties of the hydraulic oil occurs due to the presence of the undissolved air in the oil. It is known that all fluids have the capability of dissolving gases, which in the dissolved state practically does not affect its mechanical properties, [14]. As air may be present and in an undissolved state, which together constitutes a mechanical mixture, which depending on the size of the air bubbles, and both the viscosity and the type of fluid, it has a lower or a higher stability. Also, at a sudden drop in pressure, when the pressure drops below the size at which there occurred a saturation of fluid air, excess air is removed from the fluid, where the separation takes place until the re-establishment of equilibrium between the fluid and its gas phases. Typically, during operation of the hydraulic system in the oil, exposed to atmospheric pressure, there is about (3 to 6) % of undissolved air at atmospheric pressure. In certain conditions, which depend on the construction and exploitation conditions of the system, the content of the air can rise up to 15% [2]. Due to the presence of undissolved air in the oil increases the elasticity of the working environment, whose size, regardless of the dimensions of air bubbles, is as greater as their total volume. The volume modulus of elasticity of air depends on the thermodynamic compression process. If the compression is isothermal, then from the equation of isotherms, is obtained that $K = p$. If the compression is adiabatic, then from the equation of adiabatic is obtained that $K = \chi \cdot p$ (χ - the ratio of specific heat capacity and the air is $\chi = 1.4$). If such mixtures are found in the working chambers of the cylinder volume module, the elasticity due to the presence of air, will vary from volumetric elasticity modulus of hydraulic oil.

Due to the presence of air in the oil increases the elasticity of the working environment, and it will be as higher as is higher the total volume of the undissolved air, regardless of the dimensions of the air bubbles. The volume modulus of elasticity of the mixture of oil and air, at a given pressure, can be determined by using analogies with mechanical model ie., with the stiffness of two springs linked in series, Figure 5. We'll Observer the linked system (space of working chamber of the cylinder under pressure) to a part that fills oil and a part of the air that fills unresolved air describing elastic properties of working environment, in the case of a mixture of oil and air.

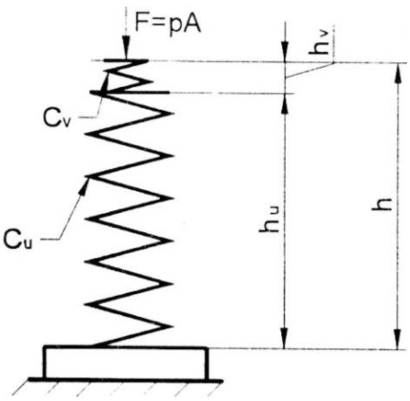

Fig. 5. The mechanical modulus to determine equivalent stiffness of the mixture of oil and air.

Stiffness (coefficient of elasticity) of compacted oil (C_u) and air (C_v), expression (15):

$$C_u = \frac{K_u \cdot A}{h_u} \quad \text{i} \quad C_v = \frac{K_v \cdot A}{h_v} \qquad (15)$$

Where certain sizes have meaning as follows: K_u, K_v – volumetric module of oil elasticity (air); A – cross-section area of cylinder and h_u, h_v – the height of the cylinder chamber that is filled by oil (air).

Equivalent stiffness of the system is given with an expression (16).

$$\frac{1}{C_e} = \frac{1}{C_u} + \frac{1}{C_v} \qquad (16)$$

How that $C_e = \frac{K \cdot A}{h}$, with replacement of expression (14) in expression (15) is obtained an expression (17):

$$K_e = \frac{K_u \cdot K_V}{K_u \cdot \frac{h_V}{h} + K_V \frac{h_u}{h}} \text{ or } K_e = \frac{K_u \cdot K_V}{K_u \cdot \frac{V_V}{V} + K_V \frac{V_u}{V}} \quad (17)$$

Where: K_e volumetric elasticity apreminksi modulus of working environment (a mixture of oil and air); V_u, V_V – a part of volumetric chamber of the cylinder that fills oil, air, and V – total volume of the cylinder chamber.

We can conclude that the decompressing process of oil in the cylinders of hydraulic presses, calculating the equivalent volume modulus of elasticity, should be regarded as adiabatic volume change modulus of elasticity of oil, isothermal state change of undissolved air (due to compression) and adiabatic state change of undissolved air during decompression.

4. MOVEMENT OF OIL PILLAR FROM A POSITION WHEN THE DEFORMATION IS EQUAL TO ZERO UNTIL THE ESTABLISHMENT OF THE BALANCED STATE OF THE DEFORMED MASS OF OIL

The total mechanical energy, which is possessed by compressed fluid is equal to the potential energy, i.e., work that is spent for its compaction (refers to the energy of fluid that is prior to compression filled the cylinder presses without additional energy of the fluid volume $A \cdot \Delta h$), izraz (18);

$$E_p = A = \int_0^{\Delta h} C \cdot x \cdot dx = C \cdot \left.\frac{x^2}{2}\right|_0^{\Delta h} = C \cdot \frac{\Delta h^2}{2} \quad (18)$$

At the moment $t_o = \frac{H}{C}$ total mechanical energy is equal to the kinetic energy of the mass of fluid

$$E_k = \int_V \frac{\rho \cdot v^2}{2} dV = \rho \cdot V \cdot \frac{1}{2} \cdot \left(\frac{p_0}{K}\right)^2 \cdot c^2 = \frac{V \cdot p_0^2}{2 \cdot K} \quad (19)$$

If we take into account that: $C = \frac{K \cdot A}{h}$, $\Delta h = h \cdot \frac{p_0}{K}$ i $V = A \cdot h$, we can see that expressions (18) and (19) are equal.

This is logical because the total mechanical energy of compressed fluid is equal to the potential energy of elastic deformation, while at the moment t_o deformation 0 and the total mechanical energy is equal to the kinetic energy of the mass of fluid. The similarity in the behavior of fluids at rest and solids exists only in load pressure.

A moment of achieving maximum force results to stop a movement of the piston, which leads to stopping the front layers of fluid. As the fluid is compressible so due to the pressure of the following layers, in a short time interval dt, it will squeeze and release the volume ($A \cdot ds$), which are filled by layers that at that moment are still moving.

If we apply the law on the maintenance of the quantity movement to the layer of thickness of fluid (ds) in the direction of movement, that is, between the two observed cross-sections, it may be an expressed by an expression (20).

$$\frac{dK_K}{dt} = A \cdot \Delta p \quad (20)$$

Product of $(A \cdot \Delta p)$ is the total pressure force in the direction of movement, while the mass force of gravity can hardly be neglected due to its insignificant impact. Since the rate of all layers of fluid at a time t_o is equal $\frac{p_0}{K} \cdot C$, we can still express the expression (21).

$$dK_k = v_0 \cdot dm = \rho \cdot \frac{p_0}{K} \cdot C \cdot A \cdot ds \quad (21)$$

From expression (18) with the replacement of values from expression (21) is obtained an expression (22);

$$\Delta p = \rho \cdot \frac{p_0}{K} \cdot C \cdot \frac{ds}{dt} = \rho \cdot \frac{p_0}{K} \cdot C = \rho \cdot \frac{p_0}{K} \cdot \frac{K}{\rho} = p_0 \quad (22)$$

In the next moment will stop the next layer which will be compressed under the pressure of other layers, etc. Thus, fully increases the pressure in the fluid, starting from the hood with the speed $c = \frac{ds}{dt}$. At the same time, assuming that the piston of cylinder is motionless (which in practice is not the case, but because of the theoretical analysis of the decompression is useful to assume), due to the motion of fluids with the speed $\frac{p_0}{K} \cdot C$, a layer of fluid in the observed point will tend to be separated from the piston. In this case a gap would be formed between the piston and the fluid to be filled in with the vapor of fluid. However, as the piston is moveable there will be a reduction of pressure in the fluid layer on the verge of piston for (equation (23)).

$$p_v = \frac{m_k \cdot g}{A} \quad (23)$$

Where are: p_v - vacuum and m_k - mass of the piston with the tool (in this we neglect friction movement of the piston in the guide rails, which for the purpose of analysis to occur in decompression of fluid in the cylinder is not very important). How this pressure is regularly lower than the saturation pressure at which the fluid evaporation occurs, the piston will start moving vertically upwards. Both pressure disorders (increase in pressure on the border with hood p_0 and reduce in pressure on the border of piston p_v) will be transmitted through the fluid simultaneously in opposite directions at the speed of sound through the fluid, i.e. with the speed c. At the time of establishment of the current balanced state $\left(t_1 = \frac{H}{c}\right)$ the pressure in fluid will be $p_1 = p_0 - p_v$. The total energy of elasticity fluid will be less than the energy calculated by formula (17) for the size of the potential energy of the piston with tool $E_{pk} = m \cdot g \cdot \Delta h_1$. However, how is $p_0 >> p_v$ and the energy of elasticity fluid is much higher than the potential energy of the piston, so we may consider that $\Delta h_1 = \Delta h$. In the next cycle there would be a movement of the piston vertically downwards and the piston stroke to the workpiece or the machine (press).

5. MODELING OF DECOMPRESSION OF THE COMPRESSED OIL IN WORKING CHAMBERS OF THE CYLINDER

The decompression process must be controlled in order to reduce the speed of movement of the particles of the working fluid, and thus slowed down the process of transformation of undissolved air in dissolved. This is achieved by draining of excess oil through a precisely defined choke. For the mathematical description of a surplus of mineral oil from the hydraulic cylinder during decompression, may use the model, Figure 6.

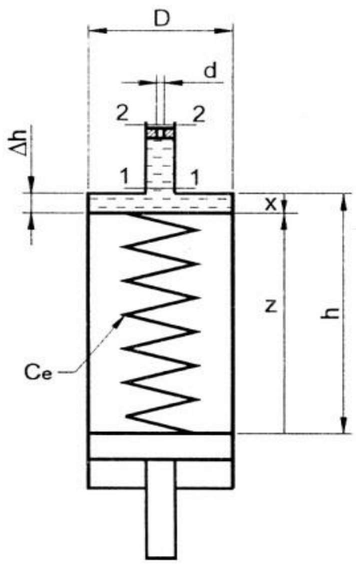

Fig. 6. Model of oil leakage in decompression

Leakage of "excess" oil from the cylinder during decompression can be treated as incompressible fluid leakage from the tank (cylinder), volume V, under the action of the spring stiffness C. As the process is non-stationary vase between the oil pressure and speed on the section of the cylinder, determined by coordinate x, and the output cross-section of jet oil (2-2), is presented by Bernoulli equation for one-dimensional unsteady flow of a perfect fluid.

$$\frac{p}{\rho \cdot g} + \frac{v^2}{2 \cdot g} = \frac{p}{\rho \cdot g} + \frac{v^2}{2g} + \int \frac{\partial v}{\partial t}\, ds \tag{24}$$

The equation of continuity:

$$v_x \cdot \frac{D^2 \pi}{4} = v_2 \cdot \frac{d^2 \pi}{4} \tag{25}$$

Here is: p – absolute pressure in the cylinder, v_x – speed of movement of the in the cylinder on the surface of coordinate x, p_2 – the pressure of the environment through which a jet is running out, v_2 – the speed of movement of the oil at the outlet of the nozzle for the jet-section with the flattened streamlines (vein of the contact), D – the inner diameter of chamber of the working cylinder exposed to pressure and D_2 – the diameter of jet for the jet-section with the flattened streamlines (vein of the contact).

The application of the form (24) and (25) and performed analysis, the change of the pressure in the cylinder during decompression can be described by the derived expression (26).

$$t = -\frac{D^2}{\mu \cdot d^2} \int_{p_0}^{p} \frac{1}{\sqrt{\frac{2}{\rho}\sqrt{p-p_2}}} \left[\frac{h \cdot K_{sa}}{\left(\frac{K_{ga}}{K_{sa}+9{,}5 \cdot (p-p_a)}\right)^{0{,}894737} \cdot [K_{sa}+9{,}5(p-p_a)]^2} + \frac{h_{va}}{\chi} p_o^{\frac{1-\chi}{\chi}} p_a \left(\frac{1}{p}\right)^{\frac{\chi+1}{\chi}} \right] \cdot dp \tag{26}$$

Here is: p_a – the working fluid exposed to the effects of the atmosphere pressure; K_{sa} – the value of volumetric modulus of oil elasticity (as a working fluid) for the working temperature of the oil at p_a , h_{va}- a part of the height of cylinder occupied by the undissolved air in oil at p_a.

In carrying out of this equation are ignored any losses in flow in addition to the losses of the flow of energy through the choke. Based on the derived expressions can be made calculation of time changes, i.e., the speed of pressure drop in defined constructional conditions and at different contents of the undissolved air and the operating parameters of the cylinder.

5. CONCLUSIONS

Based on the aforementioned it can be concluded that the energy of compressed (deformed) oil is very large and that during the decompression occurred the adverse consequences in the work of the presses (hydraulic stroke, striking of piston with the tool to the workpiece, etc.). In order to avoid this kind of process of draining of the excess fluid from the cylinder presses (or "spring" discharge of liquid that remains in the cylinder) after the end of the technological cycle, it should be carried out under the control. This is achieved by draining the fluid through a clearly defined area of the choke, respectively they must be of appropriate diameter. For an accurate determination of its values should be taken all of the above effects or use the appropriate nomograms.

REFERENCES

[1] Applehans, E.A., Pressure drop in hydraulic hose. Machine Design, vol. 55, no. 24, 1983, p.117–119.
[2] Bair, S., Michael, P., Modelling the pressure and temperature dependence of viscosity and volume for hydraulic fluids, International Journal of Fluid Power, vol. 11, no. 2, 2010, p.37–42.
[3] Desantis, M.J.,Rakowsky, E.L., Experimental Investigation of a High-Pressure Hydraulic Fluidic Vortex Rate Sensor, 1970 In SAE Technical Papers.
[4] Gardinier, J.D., Hydraulic pressure during fluid flow regulates purinergic signaling and cytoskeleton organization of osteoblasts, Cellular and molecular bioengineering, vol. 7, no. 2, 2014, p. 266–277.
[5] Giusca, C.L., Severn, I., Greenwood, J., The influence of hydraulic fluids on pressure balance calibration results, Journal of Physics: Conference Series, vol. 121, no. 15, 2008, p.152.
[6] Hanly, F.J., Fluids for high-pressure industrial hydraulic systems, In SAE Technical Papers, 1967.

[7] Hu, M., Dynamic hydraulic fluid stimulation regulated intramedullary pressure, Bone, vol. 57, no. 1, 2013, p. 137–41.
[8] Karjalainen, J.P., Karjalainen, R., Huhtala, K., Measuring and modelling hydraulic fluid dynamics at high pressure - Accurate and simple approach, International Journal of Fluid Power, vol. 13, no. 2, 2012, p.51–59.
[9] Reichel, J., Hydraulische antriebe im betrieb mit druckflussigkeiten HFC, Olhydraulik und Pneumatik, vol. 35, no. 11, 1991, p. 850–852 and 854.
[10] Tat'kov, V.V., Hydraulic drive performance in the injection mechanism of pressure diecasting machines, Soviet Castings Technology (English Translation of Liteinoe Proizvodstvo), vol. 6, 1986, p. 43–46.
[11] Wadekar, V.V., Hydraulic characteristics of flow boiling of hydrocarbon fluids: Two-phase pressure drop, Heat Transfer Engineering, vol. 33, no. 9, 2012, p. 786–791.
[12] Wahl, M., Komponenten der mobilhydraulik und druckflussigkeiten auf dem prufstand, Olhydraulik und Pneumatik, vol. 43, no. 7, 1999.
[13] Winer, W.O., The mechanical properties of fluids in high pressure hydraulic systems, Proc. 30th nat. Conf. On fluid power (Philadelphia Civic Centre), vol. 28, 1974, p. 41.
[14] Zhang, W.B., Tian, Y.Y., Li, H., Preliminary observation on the interstitial fluid pressure of low hydraulic resistance channel along meridians, Yiyong Shengwu Lixue/Journal of Medical Biomechanics, vol. 26, no. 1, 2011, p. 29–33.