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EFFECT OF BULK MODULUS OF FLUID ON THE DYNAMIC BEHAVIOR OF THE HYDRAULIC SYSTEM

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ABSTACT: The bulk modulus is the physical characteristics of the fluid, which mainly affects dynamic characteristics of the hydraulic system. The value of bulk modulus depends on the state of fluid (pressure and temperature) and thermodynamic change of state (isothermal or adiabatic).In the most commonly used hydraulic fluid - mineral hydraulic oil - a significant impact on changing the bulk modulus has the presence of undissolved air in the oil. This paper analyses the effect bulk modulus has on the elastic properties of the hydraulic fluid and the dynamic behavior of the hydraulic system.
Keywords: bulk modulus of fluid, pressure, temperature, stiffness of a hydraulic spring

1. INTRODUCTION

Liquids, like solids, have the property of elasticity. Under the influence of the pressure, liquid behaves like a solid body and any change in pressure corresponds to the appropriate change in volume. Compressibility is defined by the equation

$$\frac{dV}{V} = -\frac{dp}{K}, \qquad (1)$$

where K is bulk modulus and, for hydraulic oils without undissolved air, the value of bulk modulus depends on the pressure, temperature and thermodynamic change of state.

Elastic properties of hydraulic oil can be expressed by coefficient of elasticity [1]

$$c = -\frac{dF}{dh} = -\frac{Adp}{dh} = \frac{A\frac{dV}{V}K}{dh} = \frac{KA}{h} = \frac{KF}{hp}, \qquad (2)$$

where: h – height of column of fluid in the cylinder (the cylindrical container), p - pressure, $F = pA$ - force of pressure.

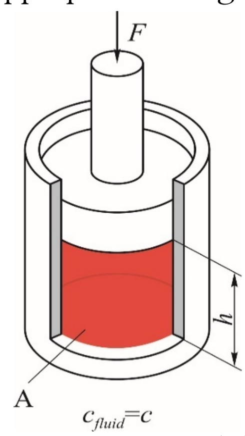

Figure 1. Compressibility of fluid

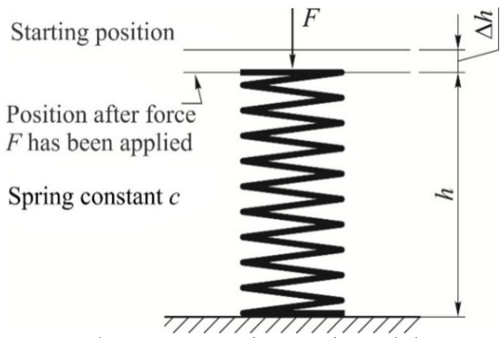

Figure 2. Mechanical model

The compressed oil in the cylinder fits the following mechanical model.

If we disregard the change of bulk modulus K, then coefficient of elasticity c is constant, and the deformation of the spring (reduction of the column height of hydraulic fluid) is given by

$$\Delta h = \frac{F}{c} = \frac{pA}{\frac{KA}{h}} = \frac{hp}{K}. \qquad (3)$$

2. ISOTHERMAL BULK MODULUS

Isothermal bulk modulus is characterized by the change in density (volume) of fluid under constant temperature

$$K_T = \rho\left(\frac{\partial p}{\partial \rho}\right)_T = -V\left(\frac{\partial p}{\partial V}\right)_T . \qquad (4)$$

Change of isothermal bulk modulus, in table 1 and Figure 3, is given for a mineral hydraulic oil HM 46 [2]. As value of bulk modulus depends, almost exclusively, from chemical structure, this oil can be used as a representative oil for a wide range of mineral hydraulic oils that are used in practice. [1], [2]

Table 1. Isothermal bulk modulus of mineral hydraulic oil

Absolute pressure p [bar]	K_T [bar]							
	15°C	20°C	30°C	40°C	50°C	60°C	80°C	100°C
1	16953	16514	15693	14940	14246	13605	12460	11465
21	17142	16702	15878	15120	14423	13778	12625	11623
41	17332	16890	16062	15301	14600	13952	12791	11781
61	17521	17078	16247	15482	14778	14125	12957	11941
81	17711	17266	16431	15664	14956	14300	13125	12101
101	17900	17454	16617	15846	15134	14475	13293	12262
141	18280	17831	16988	16211	15493	14827	13631	12587
181	18659	18208	17360	16577	15853	15181	13972	12915
201	18849	18397	17546	16761	16034	15359	14144	13081
241	19229	18774	17919	17129	16397	15716	14489	13414
281	19608	19152	18294	17499	16762	16076	14837	13750
301	19798	19342	18481	17685	16945	16256	15012	13919
401	20748	20289	19422	18616	17866	17166	15897	14777
501	21698	21238	20367	19555	18797	18088	16797	15653

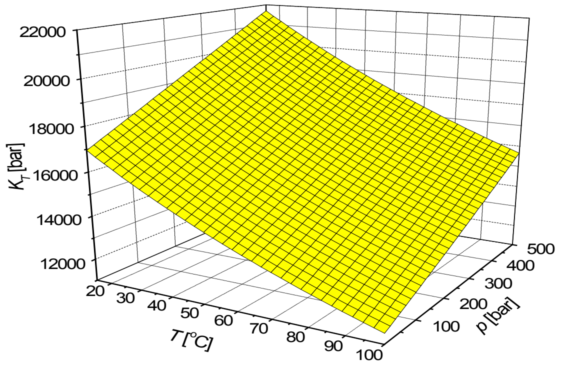

Figure 3.Isothermal bulk modulus

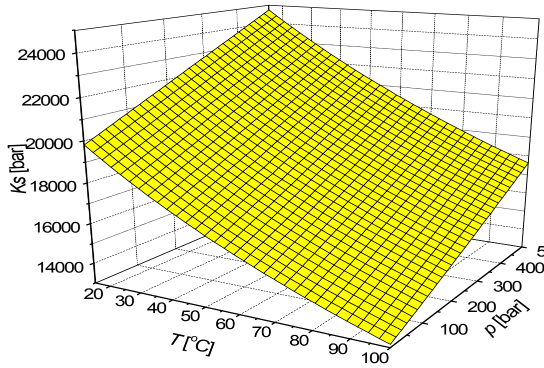

Figure 4.Adiabatic bulk modulus

Table 2. Adiabatic bulk modulus of mineral hydraulic oil [2]

Absolute pressure p [bar]	K_S [bar]							
	15°C	20°C	30°C	40°C	50°C	60°C	80°C	100°C
1	19806	19262	18248	17323	16477	15699	14319	13131
21	20003	19457	18441	17513	16663	15882	14494	13300
41	20199	19653	18634	17703	16851	16066	14671	13469
61	20396	19848	18827	17894	17038	16250	14848	13639
81	20592	20044	19021	18085	17226	16435	15027	13811
101	20789	20240	19214	18276	17415	16620	15205	13983
121	20985	20435	19408	18468	17604	16807	15385	14156
161	21378	20827	19797	18852	17983	17180	15747	14504
201	21770	21219	20187	19230	18365	17557	16112	14857
241	22163	21611	20577	19626	18748	17935	16480	15213
261	22359	21807	20772	19820	18940	18126	16665	15392
301	22752	22200	21164	20209	19326	18508	17037	15754
401	23734	23184	22148	21189	20300	19473	17981	16672
501	24718	24171	23137	22178	21285	20452	18942	17612

3. ADIABATIC BULK MODULUS

Adiabatic bulk modulus is characterized by the change in density (volume) of fluid in thermodynamic processes without exchange of heat

$$K_S = \rho\left(\frac{\partial p}{\partial \rho}\right)_S = -V\left(\frac{\partial p}{\partial \rho}\right)_S , \qquad (5)$$

$$K_S = \frac{c_p}{c_v} K_T \,. \tag{6}$$

where: c_p – specific heat capacity at constant pressure, c_v – specific heat capacity at constant volume.

Unlike static or isothermal bulk modulus, which is significant for the relatively slow compression processes, adiabatic bulk modulus is relevant for the analysis of the speed of propagation of pressure, sudden unloading chambers under pressure and other processes where changes of state of oil occurs relatively quickly.

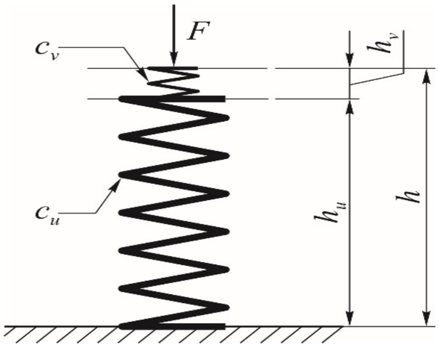

Figure 5. Mechanical model for calculating the equivalent stiffness of the mixture of oil and air

4. DISSOLUTION OF AIR IN MINERAL OIL

All liquids have ability to absorb air, which in dissolved state does not impact liquid mechanical property. Volume of gas which could be absorbed by the liquid, till the liquid reaches its saturation, depends on pressure, temperature, type of gas and type of liquid. Bunsen`s coefficient is used to rate gas dissolving ability in liquid. The Bunsen`s coefficient is defined as volume of gas on atmospheric pressure and temperature of 0°C, which could be dissolved in unit volume of liquid. In mineral oils which are used in hydraulic systems, the value of air Bunsen`s coefficient is $\alpha_b \approx 0.09$ .[3] At atmospheric pressure and temperature 0-100°C the volume of air which could be dissolved in oil is practically constant, so the Bunsen`s coefficient is constant too. The volume of air that can be dissolved in some additional volume of mineral oil until pressure of 300 bar is:

$$V_g = V_u \alpha_b p \,, \tag{7}$$

where: V_g - volume of dissolved air, V_u - volume of oil, p - absolute pressure of air in oil.

During operation of hydraulic system, oil usually contains 3-6% of undissolved air (at atmospheric pressure). By certain conditions, which depend on construction and exploitation conditions of system, the volume of undissolved air in oil can rise up to 15%. [4]

5. BULK MODULUS OF MIXTURE OF MINERAL HYDRAULIC OIL AND AIR

Increased working environment elasticity, caused by presence of undissolved air in oil, will increase with the increase of total volume of undissolved air, independent of air bubble dimension.

The analysis will be done using hydraulic cylinder example with remark that the obtained results for equivalent stiffness do not depend on pressure chamber shape.

The bulk modulus of mixture of oil and air, at given pressure, could be determined by using analogy with mechanical model, separating the whole volume of pressurized cylinder chamber in two parts: part filled with oil and part filled with undissolved air. As bulk modulus is used for description of elasticity properties of working environment, in the case of mixture of oil and air, equivalent stiffness of working environment can be determined as equivalent stiffness of two springs conceded in series. From equation (2) can be seen that stiffness (bulk modulus) of oil is

$$c_u = \frac{K_u A}{h_u} \,, \tag{8}$$

where: K_u - bulk modulus of oil, A - cylinder cross-section area, h_u - part of the cylinder height that is filled with oil, while stiffness (bulk modulus) of air is

$$c_v = \frac{K_v A}{h_v} \,, \tag{9}$$

where: K_v - bulk modulus of air, h_v - part of the cylinder height that is filled with air.

Equivalent stiffness is given by equation:

$$\frac{1}{c_e} = \frac{1}{c_u} + \frac{1}{c_v} \,, \tag{10}$$

as

$$c_e = \frac{K_E A}{h} \,, \tag{11}$$

We get,

$$K_E = \frac{K_u K_v}{K_u \frac{h_v}{h} + K_v \frac{h_u}{h}} \,, \text{ respectively } K_E = \frac{K_u K_v}{K_u \frac{V_v}{V} + K_v \frac{V_u}{V}} \tag{12 - 13}$$

where: K_E–bulk modulus of working environment (mixture of oil and air), V_u–cylinder volume part that is filled with oil, V_v–cylinder volume part that is filled with air, V–total cylinder volume.

6. EQUIVALENT BULK MODULUS OF MIXTURE OF MINERAL HYDRAULIC OIL AND AIR UNDER ADIABATIC CHANGE OF STATE

If the change of air state is adiabatic, then the volume of undissolved air in oil, depending on pressure, is given by equation

$$V_v = \left(\frac{p_a}{p}\right)^{\frac{1}{\kappa}} V_{va} . \qquad (14)$$

Equivalent bulk modulus of oil and air mixture for adiabatic change of state of oil at compression and adiabatic change of state of undissolved air in oil, is then

$$K_{SE} = \frac{K_S \kappa p}{K_S \dfrac{\left(\frac{p_a}{p}\right)^{\frac{1}{\kappa}} V_{va}}{\left(V_u + \left(\frac{p_a}{p}\right)^{\frac{1}{\kappa}} V_{va}\right)} + \kappa p \dfrac{V_u}{\left(V_u + \left(\frac{p_a}{p}\right)^{\frac{1}{\kappa}} V_{va}\right)}} . \qquad (15)$$

Adiabatic compression of air bubbles that are in oil leads to their significant warming. The connection between temperature and pressure, at adiabatic change of state of air is given by equation:

$$T_{A2} = \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} T_{A1} \ [\mathrm{K}], \qquad (16)$$

where: T_{A1} i p_1-absolute temperature and pressure at the beginning of the process, T_{A2} i p_2 - absolute temperature and pressure at the end of the process.

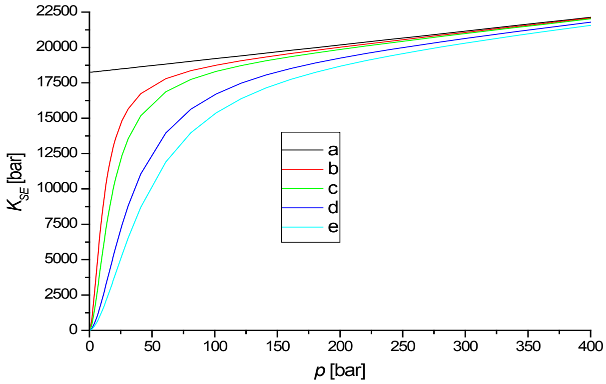

Figure 6. Equivalent adiabatic bulk modulus: a) without the presence of undissolved air; b) 0.5%undissolved air; c) 1% undissolved air; d) 3% undissolved air; e) 5% undissolved air

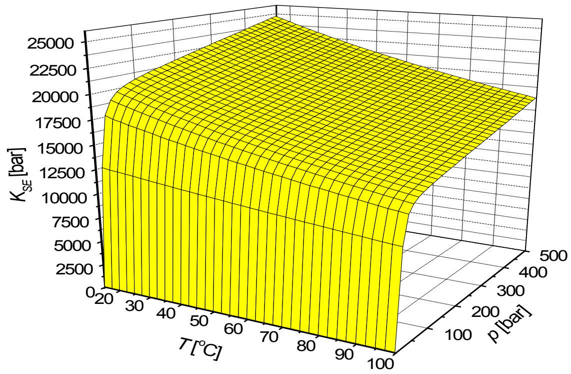

Figure 7.Equivalent adiabatic bulk modulus depending on the pressure and temperature in the presence of 1% undissolved air in the oil

It can be seen that at adiabatic compression of air bubbles that are in hydraulic oil, their temperature can increase significantly (e.g. at adiabatic compression of air with starting temperature of 30°C, from atmospheric to 70 bar pressure, temperature of air increases to approximately 75°C). This causes forming of flammable oil-air aerosols, which in case of ignition leads to very high oil temperature. The indicator for such processes is black colored hydraulic oil (similar to used oil from internal combustion engines) and burning smell.

6. CONCLUSION

- Working environment elasticity has significant influence on work efficiency and dynamic behavior of hydraulic system.
- Presence of undissolved air in hydraulic oil, especially in region of low pressure (under 20 bar) leads to significant change of bulk modulus.
- Undissolved air in hydraulic fluid causes action delay in hydraulic components (hydro motors and cylinders) and decreases their self-oscillation stability. It is similar to mass-spring mechanical system, where stiffness (elasticity) of working environment determines behavior of working components oscillations.
- Working environment elasticity is very important if sudden depressurizing of hydraulic cylinder chambers occurs (especially for cylinders with large working volume). If that is the case and if the depressurizing process is uncontrolled, the hydraulic hammer will occur.

Note: This paper is based on the paper presented at The 12th International Conference on Accomplishments in Electrical and Mechanical Engineering and Information Technology – DEMI 2015, organized by the University of Banja Luka, Faculty of Mechanical Engineering and Faculty of Electrical Engineering, in Banja Luka, BOSNIA & HERZEGOVINA (29th – 30th of May, 2015).

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