Serbian Tribology Society

SERBIATRIB '11

12th International Conference on Tribology

Faculty of Mechanical Engineering in Kragujevac

Kragujevac, Serbia, 11 – 13 May 2011

ANALYSIS OF CHANGES OF BULK MODULUS OF MINERAL OIL – EFFECTS ON THE DYNAMIC BEHAVIOR OF HYDRAULIC ACTUATORS

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Abstract: *When setting up the equations that describe the dynamic behavior of hydraulic actuators, it is important to know the physical properties of working fluid and the mathematical description of change of these properties with changing pressure and temperature. Although the compressibility of liquids in the practical analysis of the flow can usually be ignored, in dynamic analysis of work of hydraulic components fluid must be viewed as an elastic medium which is deformed at rest with changing pressure and temperature. In addition to the dynamic behavior of hydraulic actuators largely influenced by the presence undissolved air in the hydraulic fluid. Even in very small quantities, which can not be avoided in hydraulic systems, usdissolved air in the hydraulic fluid significantly changes the elastic properties of the working fluid, affects the transmission speed of pulses of change of pressure, leading to delay response of actuators and others.*

In this paper, change of value of effective bulk modulus of mixture of mineral oil and dissolved air is given on the basis of data obtained from manufacturers and experimental data obtained in the analysis of decompression of oil in the hydraulic cylinders.

Keywords: *bulk modulus, pressure, temperature, undissolved air, decompression, dynamic behaviour*

1. INTRODUCTION

Besides the basic functions that transmit energy in the hydraulic system from the place of transformation of mechanical into hydraulic energy (pump) to a place of transformation hydraulic into mechanical energy (cylinder, rotary or oscillating motor), hydraulic oils and fluids, perform a few extra features such as lubrication of all places contacts within the hydraulic components, corrosion protection, download the generated heat and, later, its transmission to the environment, and others.

In accordance with the requirements for hydraulic fluid that sets components, system, environment and conditions of exploitation has formulated a series of structural and quality different hydraulic fluids. In practice, as hydraulic fluids are commonly used mineral oils. They are classified into six qualitative levels (HH, HL, HM, HR, HV and HG), but now in the hydraulic systems used exclusively oils classes HM and HV. This is essentially the same quality class of oil, noting that in oil class HV value of viscosity index increased relative to oil HM.

The value of the bulk modulus of mineral oils for hydraulic systems depends primarily on the chemical composition of base oil. [1]

Mineral base oils are composed of complex molecules of carbon-hydrogen. According to the domination of the representation of certain carbon-hydrogen in oil, mineral oil can be divided into paraffinic, naphthenic and mixed. Hydraulic oil is almost completely derived from base oil of paraffinic structure, and the naphthenic oil, because of reduced availability, used only in special conditions of application. [1]

Paraffin carbon-hydrogens can be straight (n-paraffins) and branchy (iso-paraffins) and have the general formula C_nH_{2n+2}.

Molecular structure and weight carbon-hydrogens affect the physical and chemical behavior of mineral oil. Molecules of carbon-hydrogens in paraffin oil contain 20-50 carbon atoms and have the average molecular weight of 350-550. [2]

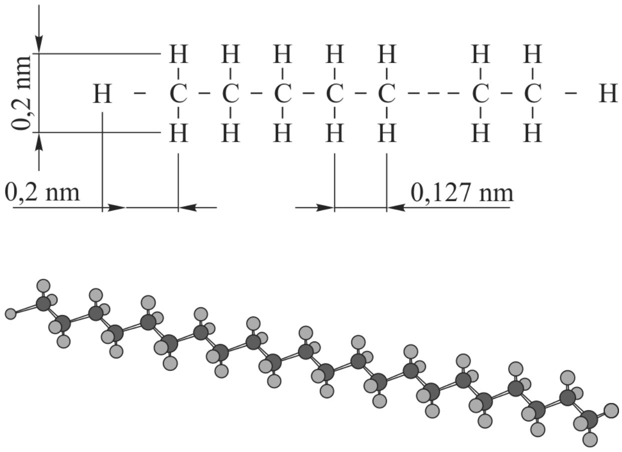

Figure 1. N-paraffins

In Figure 2.1 are given the distance between atoms, in nanometers, into paraffin molecules of carbon-hydrogen. Given the number of carbon atoms in a molecules can be calculated that the length of the molecules n-paraffin 3-6.75 nm (0.003-0.00675 μm). In iso-paraffin molecules length is smaller (because a certain number of atoms of carbon and hydrogen form lateral chains), but the width is higher than the n-paraffins.

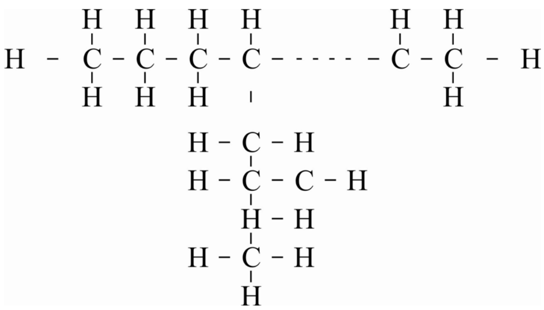

Figure 2. Iso-paraffins

The value of bulk modulus in this paper is given for mineral hydraulic oil HM 46. As the value of the bulk modulus depends almost exclusively on the chemical structure of liquids, this oil can serve as a representative for a wide range of mineral hydraulic oils used in practice. [3]

The accuracy of this statement is confirmed by experimental data obtained by measurements in the analysis process decompression of mineral oils in the cylinders of hydraulic presses. [4]

2. COMPRESSIBILITY – THE ELASTICITY OF HYDRAULIC FLUID

Compressibility of fluid are quantitatively expressed in differential form,

$$\frac{dV}{V} = -\frac{dp}{K}, \tag{1}$$

where K is a bulk modulus (volumetric elastic modulus) and for the hydraulic oil without undissolved air its value depends on the pressure, temperature and thermodynamic method of process.

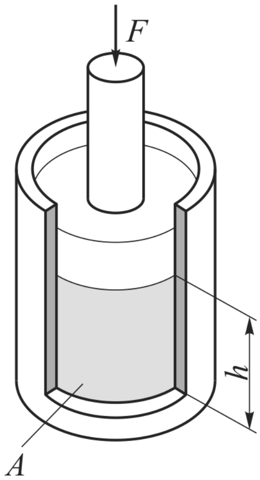

Figure 3. Compressibility of fluid

Elastic properties of liquids can be expressed by the coefficient of elasticity which can be generally given pattern,

$$c = -\frac{dF}{dh} = -\frac{A dp}{dh} = \frac{A\frac{dV}{V}K}{dh} = \frac{KA}{h} = \frac{KF}{hp}, \tag{2}$$

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

3. ISOTHERMAL BULK MODULUS OF MINERAL OIL

Isothermal bulk modulus characterizes a change of density (volume) of fluid at constant temperature

$$K_T = \rho\left(\frac{\partial p}{\partial \rho}\right)_T = -V\left(\frac{\partial p}{\partial V}\right)_T. \tag{3}$$

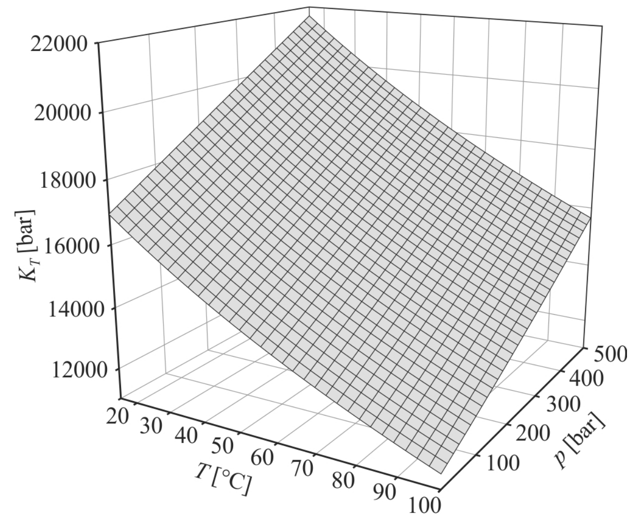

Figure 4. Isothermal bulk modulus of mineral oil

Change the isothermal bulk modulus as function of pressure and temperature, in Figure 4, is given for mineral hydraulic oil viscosity class HM 46, based on data obtained from the manufacturer. [3]

4. ADIABATIC BULK MODULUS OF MINERAL OIL

Adiabatic bulk modulus characterizes a change of density (volume) of fluid in thermodynamic processes without exchange of heat. Unlike the isothermal or static bulk modulus, which is significant for relatively slow processes of compression, adiabatic bulk modulus is important for analysis of the speed of propagation of the pulses of pressure, sudden relief of chambers under pressure, and other processes where a change in oil condition occurs relatively quickly

$$K_S = \rho \left(\frac{\partial p}{\partial \rho} \right)_S = -V \left(\frac{\partial p}{\partial V} \right)_S , \qquad (4)$$

$$K_S = \frac{c_p}{c_v} K_T , \qquad (5)$$

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

Change the adiabatic bulk modulus as function of pressure and temperature, in Figure 5, is given for mineral hydraulic oil viscosity class HM 46, based on data obtained from the manufacturer. [3]

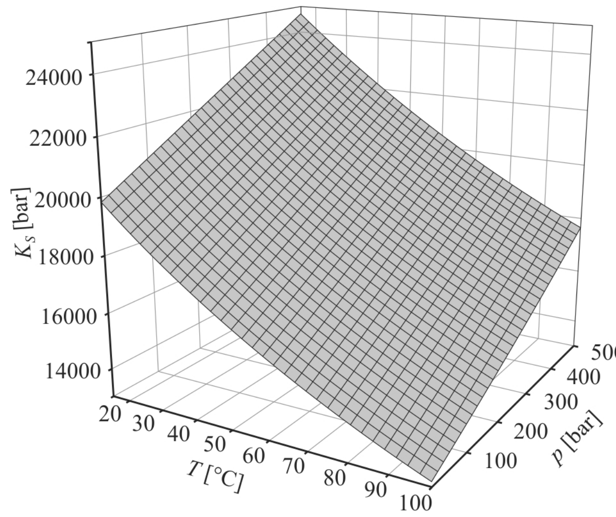

Figure 5. Adiabatic bulk modulus of mineral oil

5. SPEED OF PROPAGATION OF SMALL DISTURBANCES (SPEED OF SOUND) IN MINERAL OIL

Speed of response on the change of pressure in the hydraulic system is very important in a very dynamic process, where significant speed and accuracy of the positioning of hydraulic actuators.

Speed of propagation of the pulses of pressure through a fluid is equal to the speed of sound through the fluid and depends on adiabatic bulk modulus and fluid density

$$c_z = \sqrt{\frac{K_S}{\rho}} . \qquad (6)$$

Based on data for the adiabatic bulk modulus K_S and density ρ were calculated data for the velocity of sound for mineral oil HM 46 and give the following diagram.

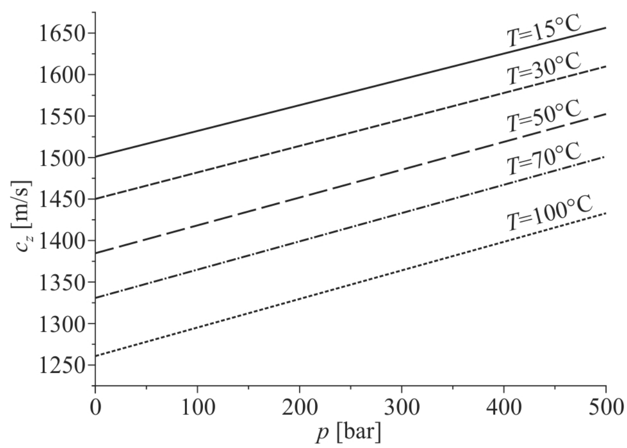

Figure 6. Speed of sound in mineral oil

6. EFFECTIVE BULK MODULUS OF THE MIXTURE OF MINERAL OIL AND UNDISSOLVED AIR

Increased flexibility of working fluid due to the presence undissolved air in the oil will be greater because of the higher volume undissolved air, regardless of the size of air bubbles.

The analysis will be done on the example of a hydraulic cylinder, noting that the results obtained for equivalent compression module does not depend on the type chamber under pressure. Effective bulk modulus of the mixture of oil and air, at a given pressure, can be determined using the analogy of the mechanical model, dividing the total space of the cylinder pressure chamber to the part that meets the oil and the part that meets the undiluted air. As an effective bulk modulus serves to describe the elastic properties of the working fluid, in the case of a mixture of oil and undissolved air, the equivalent stiffness of the working fluid can be defined as the equivalent stiffness of two serially connected springs.

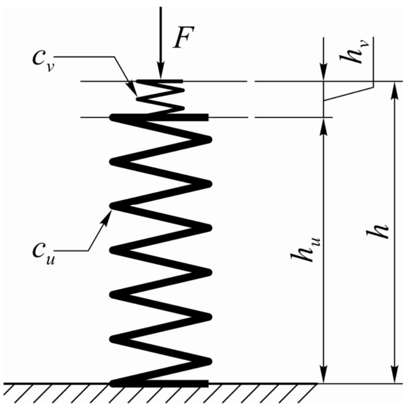

Figure 7. Mechanical model for calculating the equivalent stiffness of the mixture of oil and air

The stiffness (coefficient of elasticity) oil is given by pattern

$$c_u = \frac{K_u A}{h_u}, \tag{7}$$

where:
K_u – bulk modulus of oil,
A – the cross-section of the cylinder and
h – height of the cylinder chamber that is filled by oil,
while the stiffness (elasticity coefficient) air is given by

$$c_v = \frac{K_v A}{h_v}, \tag{8}$$

where:
K_v – bulk modulus of air and
h_v – height of the cylinder chamber that is filled by air.

The equivalent stiffness is given by

$$\frac{1}{c_e} = \frac{1}{c_u} + \frac{1}{c_v}. \tag{9}$$

As

$$c_e = \frac{K_E A}{h}, \tag{10}$$

substituting expressions (2.23) (2.24) and (2.27) into (2.25), we get

$$K_E = \frac{K_u K_v}{K_u \frac{V_v}{V} + K_v \frac{V_u}{V}}, \tag{11}$$

where:
K_E – effective bulk modulus (mixture of oil and air),
V_u – part of the volume of the cylinder chamber that is filled by oil,
V_v – part of the volume of the cylinder chamber that is filled by air and
V – total volume chamber cylinder.

7. AN EXAMPLE OF EFFECTIVE BULK MODULUS OF MIXTURE OF HYDRAULIC OIL AND UDISSOLVED AIR UNDER ADIABATIC CHANGE OF STATE OIL AND ISOTHERMAL CHANGE OF STATE UNDISSOLVED AIR

Experiments carried out to analyze the process of decompression mineral hydraulic oil in hydraulic presses have shown that due to relatively rapid changes in the conditions of process, change of state of oil can be considered adiabatic. Regardless of the adiabatic change of state, because of the significant heat capacity, oil temperature is slightly changed, so that the change of state of dispersed undissolved air bubbles in oil can be considered isothermal. [4]

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

$$V_v = \left(\frac{p_a}{p}\right) V_{va}. \tag{12}$$

The effective bulk modulus of the mixture of oil and undissolved air, by inserting the expression (12) into (11), is

$$K_E = \frac{K_S p}{K_S \frac{\left(\frac{p_a}{p}\right) V_{va}}{\left(V_u + \left(\frac{p_a}{p}\right) V_{va}\right)} + p \frac{V_u}{\left(V_u + \left(\frac{p_a}{p}\right) V_{va}\right)}} . \quad (13)$$

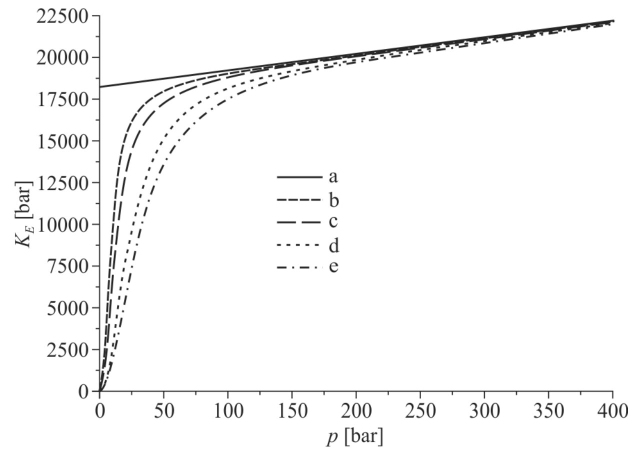

Figure 8. Effective bulk modulus at oil temperature of 30°C: a) the absence of undissolved air, b) 0.5% undissolved air, c) 1% undissolved air, d) 3% undissolved air; e) 5% undissolved air

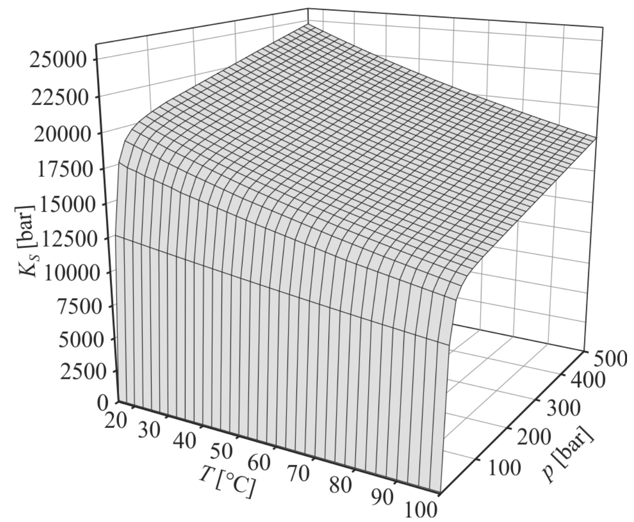

Figure 9. Effective bulk modulus depending on the pressure and temperature in the presence of 1% undissolved air in mineral oil

8. APPLICATION OF VALUE EFFECTIVE BULK MODULUS IN THE ANALYSIS PROCESS DECOMPRESSION (UNLOADING) OF OIL IN THE HYDRAULIC CYLINDERS

Theoretically analyzes the process of unloading of hydraulic cylinders controlled by draining the oil that is released through the relief nozzle-shaped openings with sharp edges. In parallel experimental study was carried out of the process. Experiments were carried out with mineral hydraulic oil HM 22, 32, 46 and 64 and HV 46, the common values of pressure in the hydraulic systems (up to 350 bar) and standard operating temperature (from 15 to 70ºC).

Experimental verification of the theoretical model, in which the value of the effective bulk modulus was calculated by the formula (13), was shown that the process of decompression of mineral hydraulic oil can mathematically be described with great accuracy, even for small pressure when the impact undissolved air in the elasticity working fluid very large. Although during the compression and decompression of oil in the hydraulic cylinders are occurred complex processes of gradual dissolution undissolved air in the oil during compression and extraction of dissolved air from the oil during decompression, the experimental data showed that the analytical description can be counted with the presence undissolved air in the hydraulic oil from a to 3% of the total volume of the cylinder at atmospheric pressure.

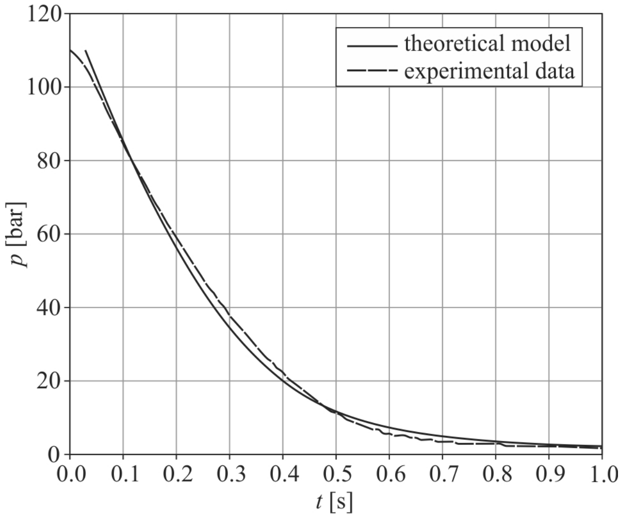

Figure 10. Change of pressure during the process of decompression of mineral oil which content 3% undissolved air at atmospheric pressure (oil temperature is 30 °C)

Figure 10 is an example of comparing experimental results with theoretical model description of the process of decompression, in which the value of the effective bulk modulus calculated by the formula (13). The experimental results in Figure 10 are provided for hydraulic cylinder diameter of 140 mm and length of stroke of 1000 mm. [4]

Controlled load shedding is done by draining the oil through a nozzle with a sharp edge diameter 2 mm. The theoretical model was calculated with undissolved air content of 3% in oil, at atmospheric pressure.

9. CONCLUSION

The value of the bulk modulus of hydraulic fluid has a large impact on the efficiency of the hydraulic system. It affects:

- Speed of propagation of the pulse pressure change in the system,
- Positioning accuracy of hydraulic actuators,
- Volumetric efficiency of pumps,
- The stability of the system according to its own fluctuations,
- The intensity of the hydraulic shock.

This paper gives the values of bulk modulus which are representative for mineral oil for hydraulic systems. The data are presented in the form of a diagram as a function of temperature and pressure. Data were checked indirectly, experimental measurements change of pressure during process decompression of mineral oil in the hydraulic cylinders.

Experimental results show that it is not possible to avoid the presence of undissolved air in the work of hydraulic systems. Comparing experimental data with theoretical model shows that in determining the effective bulk modulus can be count content of undissolved air in mineral oil in quantities of 1 to 3% at atmospheric pressure.

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