Strojniški vestnik - Journal of Mechanical Engineering 55(2009)4, 237-243
UDC 621.643

Paper received: 27.10.2008
Paper accepted: 03.04.2009

Determination of Pressure Losses in Hydraulic Pipeline Systems by Considering Temperature and Pressure

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Generally accepted methods for calculating pressure losses within flat pipelines as presented in literature and used in praxis, are based on the Reynolds number, which considers the viscosity and density of fluid, internal pipe friction coefficient, pipe geometry, and oil circulation velocity. Such an approach contains serious inconsequentiality. Namely, the only nominal values for viscosity and density are considered in the calculation, which differs substantially from real conditions. This often leads to inaccurate calculations of pressure losses.

A numerical model has been developed in the work presented in the paper. It takes into account the actual changes in density and viscosity under the current oil pressure and temperature in order to overcome the above weaknesses of standard calculation procedures. Such an approach is novel and provides new capacity for an accurate pressure drop analysis of advanced hydraulic systems.

Keywords: hydraulic pipeline, pressure losses, temperature, presure

0 INTRODUCTION

Energy dissipation due to the frictional resistance of fluid flow within a hydraulic pipeline system is represented by any decrease in pressure. The pressure loss is determined according to the well-known Darcy-Weisbach equation:

$$\Delta p = \lambda \frac{L}{d} \rho \frac{v^2}{2} \tag{1}$$

where: L – pipeline length, d – diameter of the pipe, v – the fluid flow velocity, ρ – density of the hydraulic fluid and

$$\lambda = \lambda\left(Re, \frac{\varepsilon}{d} \right)$$

friction factor λ which depends on the Reynolds number Re, and pipe roughness.

In the cylindrical tubes, the friction factor is usually determined by using the Moody diagram (Fig. 1). This diagram depicts the Reynolds number against the friction factor, and describes the corresponding fluid regimes.

The fluid flow through a pipe can be either smooth or rough, depending on flow conditions. Various factors determine the nature of flow. In principle, the flow can be stated as either laminar flow, i.e. steady, smooth flow, or turbulent flow, i.e. the flow is disturbed. From a practical point of view, the Reynolds number indicates if a flow is laminar or turbulent.

In the case of turbulent flow, the friction factor λ depends on the Reynolds number, as in the case of laminar flow as well as on the coefficient of the relative roughness – the relationship between the absolute roughness of the pipe's inner wall surface in contact with the fluid, and the diameter of the pipe (ε/d), bearing in mind that the pipe can be either perform as a smooth, rough or somewhere in-between – liminal (transitional).

Several types of empirical equations that can help to determine the friction factor can be found in literature. Some fairly useful ones are given below [1] and [2].

a) Laminar flow area at $Re < 2000$:

$$\lambda = 64/Re \tag{2}$$

b) Turbulent flow area within the smooth pipe of a hydraulic system (according to Blasius [2]) at $Re > 4000$:

$$\lambda = 0.3164/Re^{0.25} \tag{3}$$

c) Transitional flow type area within range $2000 < Re < 4000$:

$$\lambda = 3.9\ Re + 0.0242. \tag{4}$$

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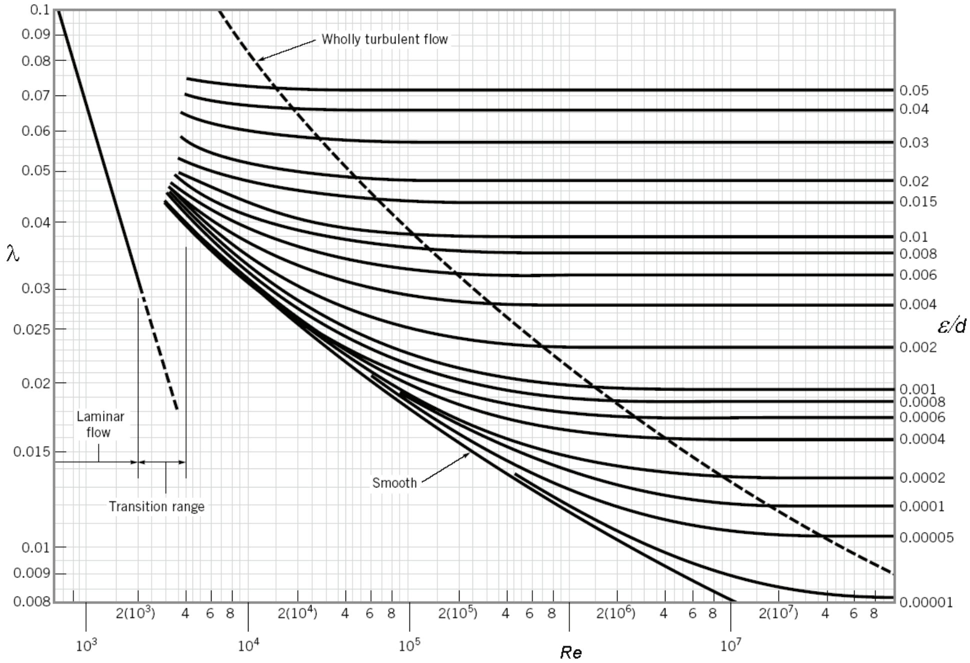

Fig. 1. *Moody diagram for the determination of flow regimes with regard to internal friction coefficient [2]*

d) The Reynolds number value can be estimated using the following equation:

$$Re = vd/\nu \tag{5}$$

where ν [m^2/s] – kinematic viscosity, d [m] – pipe diameter, v [m/s] – average fluid flow velocity.

Most of the authors [1] legitimately assume that all the hydraulic pipeline systems are smooth because:

a) Pipes are produced by precise drawing with low absolute roughness values 0.01 to 0.002 mm (average value 0.006 mm).
b) The applied Reynolds number is most often in the order of medium values, i.e. between 1000 and 20000 so the friction factor value is at the limit of what is considered smooth (the lowest curve in Moody's diagram represents smooth hydraulic pipes).

Numerical verification of the aforementioned statement is based on the calculation within the following boundary values:

a) mostly used hydraulic pipelines range in diameter from 10 to 50 mm, so that the relative roughness ε/d is within the range of

   0.0006 to 0.00012

   which is at the lower end of the relative roughness, as depicted in Moody's diagram (see Fig. 1);
b) usually fluid flow velocity v =1 to 6 m/s;
c) common kinematic viscosity at operating temperature (16 to 54)·10^{-6} m^2/s are borderline values of the optimum viscosity for the e.g. axis piston pumps.

For the borderline areas, the Reynolds number falls within the range indicated in Table 1.

Table 1. *Dependency of Reynolds number of the pipeline and fluid properties*

Dimension		Number value							
Pipe diameter	[mm]	10				50			
Flow speed	[m/s]	1.0		6.0		1.0		6.0	
Kinematic viscosity	[mm^2/s]	16	54	16	54	16	54	16	54
Reynolds number	[-]	625	185	3750	1110	3125	925	18750	5550

When analyzing the values of the Reynolds number, two conclusions can be drawn. The Reynolds number will increase with diameters $d > 50$ mm, flov speed $v > 6.0$ m/s, and kinematic viscosity $\nu < 16$ mm^2/s, whereas the Reynolds number will decrease with $d < 10$ mm, $v <1.0$ m/s and $\nu < 54$ mm^2/s.

It follows, that the friction factor of the mineral hydraulic oil-flow through hydraulic pipeline can be determined with satisfactory accuracy, using the Eqs. (2) to (4) and the pipeline of the hydraulic system may be treated as smooth.

1 INFLUENCE OF TEMPERATURE AND PRESSURE CHANGES ON PHYSICAL-CHEMICAL PROPERTIES OF HYDRAULIC FLUID

The characteristic physical values of all hydraulic fluids which have a deciding influence on the loss of energy are density ρ and viscosity ν of the fluid. Both are temperature (T) and pressure (p) dependent values: $\rho = \rho(p,T)$, $\nu = \nu(p,T)$.

2.1 Density of Fluid

Density is defined as the mass of fluid per unit volume:

$$\rho = \frac{m}{V} \tag{6}$$

where: m [kg] – mass, V [m^3] – volume.

The density of a hydraulic fluid is measured under atmospheric pressure at T = 288 K. Any increase in temperature results in increased fluid volume, whereas the fluid volume decreases according to any rise in pressure (and contrarily in the reverse order of temperature and pressure changes).

Density changes as a consequence of temperature and pressure changes can be given in the form of a total differential:

$$d\rho = \left(\frac{d\rho}{dT}\right)_p dT + \left(\frac{d\rho}{dp}\right)_T dp$$

or in a rewritten form:

$$\frac{d\rho}{\rho} = -a_p\ dT + \frac{1}{K_T} d_p \tag{7}$$

from where results α_p - volumetric temperature fluid expansion coefficient by constant pressure:

$$\alpha_p = -\frac{1}{\rho}\left(\frac{dp}{dT}\right)_p \tag{8}$$

and K_T – isothermal compression module

$$K_T = \rho\left(\frac{dp}{d\rho}\right)_T . \tag{9}$$

2.1.1 The Effect of Temperature on the Oil Density

Using the law of mass conservation ($m = \rho V = const.$) according Eqs. (8) and (9), two equivalent models can be expressed by the following equations:

$$\alpha_p = \frac{1}{V}\left(\frac{dV}{dT}\right)_p \tag{10}$$

and

$$K_T = -V\left(\frac{dp}{dV}\right)_T . \tag{11}$$

Coefficient α_p serves to define the relative change of fluid (volumetric) density. This is dependent on the mean molecular weight of the hydrocarbon. Figure 2 shows a diagram of coefficient change, as drawn-up on the bases of the tested numerical values [3].

Based on the experimentally verified Equation [4]:

$$\left(\frac{d\rho}{dT}\right)_p = -\alpha_p\ \rho = const$$

it is possible to derive an equation which describes the relationship between the hydraulic oil density for any temperature, and the atmospheric pressure, using the values that apply to the density at T = 288 K [4]:

$$\rho_x = \rho_{15}\left[1 - \alpha_{15}(T - 288)\right] \tag{12}$$

where the value of α_{15}=0.0007 is evident on the diagram in Fig. 2.

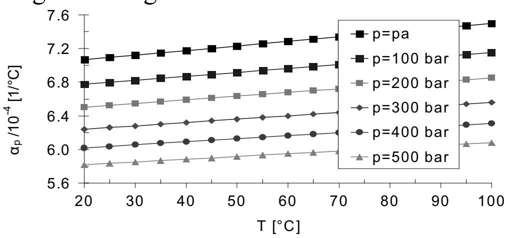

Fig. 2. *Changes in coefficient α_p underconstant pressure*

2.1.2 The Effect of Pressure on the Hydraulic Oil density

As mentioned above, the fluid volume reduces with any increase in pressure, while its density becomes greater at the same time. Compression module can be expressed in terms of the previously-stated equations:

$$K_T = \rho \left(\frac{dp}{d\rho}\right)_T = -V \left(\frac{dp}{dV}\right)_T$$

so that any alteration in density, as a function of pressure change, for both the constant values of compression module K_T and constant temperature, is worked out by the formula below:

$$\Delta\rho = \rho \frac{\Delta p}{K_T} \tag{13}$$

whereby it follows that

$$\rho_p = \rho_x + \Delta\rho = \rho_x + \rho_x \frac{\Delta p}{K_T} = \rho_x \left(1 + \frac{\Delta p}{K_T}\right). \tag{14}$$

Coefficient (K_T) change diagram modeled on the bases of the tested numeric values [2] is presented in Fig. 3.

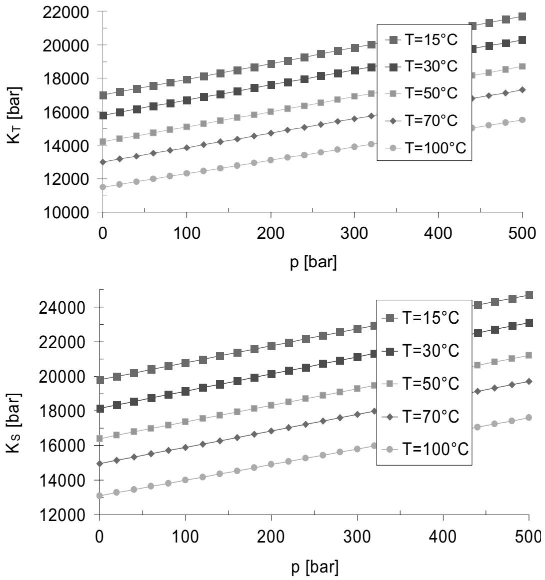

Fig. 3. *Change of isothermal (K_T) and adiabatic (K_S) compression module as a function of operating pressure and oil temperature*

2.2 Viscosity

Viscosity represents fluid resistance to shear or flow and is a measure of the adhesive/cohesive or frictional fluid's property. Used in hydraulics, there is a concept of dynamic viscosity, the value of which is determined by Newton's equation concerning parallel linear laminar flow.

$$\frac{F}{A} = \mu \frac{dv}{dx} \tag{15}$$

where: F [N] – is side force; A [m^2] – side force surface; dv/dx [1/s] – velocity of angular deformation.

Dynamic viscosity is expressed in Pascal seconds [Pa·s], which corresponds to [kg/m·s]. In technical practice, the term kinematic viscosity is used, which is defined as the ratio between dynamic viscosity and fluid density:

$$\nu = \frac{\eta}{\rho}. \tag{16}$$

2.2.1 Influence of Temperature Change on the Viscosity of the Hydraulic Oil

The kinematic viscosity of industrial oils is measured under atmospheric pressure at 40 °C. It is classified into VG viscosity classes according to the ISO standard. Hydraulic fluids of class ISO VG 46 are most frequently used in praxis. They are followed by fluids classed as VG 32, and less commonly by VG 68 or 22.

Several formulae, derived for determining viscosity as a function of temperature, can be found in relevant literature, e.g. [6]:

$$\mu = b\, e^{-a \cdot T_A} \quad \text{- according to Reynolds} \tag{17}$$

$$\mu = \frac{a}{\left(b + T_A\right)^C} \quad \text{- according to Slotte} \tag{18}$$

$$\left(\nu + a\right) = b\, d^{\frac{1}{T_A^c}} \quad \text{- according to Walther} \tag{19}$$

$$\mu = a\, e^{\frac{b}{(T_A - c)}} \quad \text{- according to Vogel.} \tag{20}$$

The coefficients *a, b, c, d* contained in the Eqs. (17) to (20) are affected by the properties of individual hydraulic fluids, with T_A signifying the absolute temperature. The most accurate among them is Eq. (20) but the more frequently used one is Eq. (19), which also forms the basis for the ASTM viscose temperature diagram's design [5].

The measurement for the change of kinematic viscosity with temperature is commonly determined by the viscosity index (VI), a non-dimensional number. Oils of faster viscosity alteration are classified as HM oils

(VI = 90), and those of slower alteration as HV oils (VI = 140).

Figure 4 shows a diagram of viscosity alteration as a function of temperature and in relation to HM oils 32, 46, and 68. The diagram represents the results of tests for oil's viscosity at 40 and 100 °C [5].

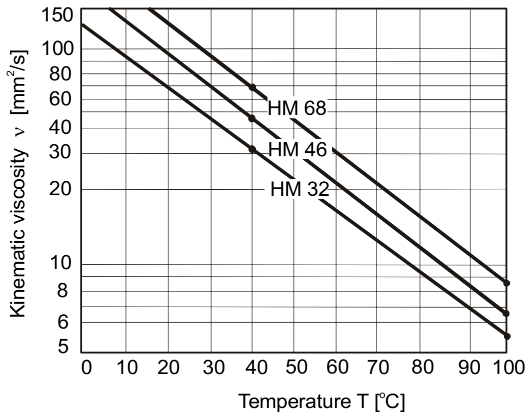

Fig. 4. *The alteration of viscosity as a function of temperature for oils HM 32, 46 and 68*

2.2.2 The Effect of Pressure on the Viscosity of Hydraulic Oils

Oil viscosity increases with any concurrent increase in pressure. The speed of this change depends on the molecular structure of the oil, meaning that the speed will be higher where the oil viscosity is lower.

Numerical value of kinematic viscosity alteration as a function of the change in pressure can be worked out in two different ways:

a) directly by kinematic viscosity calculation:

$$\nu_p = \nu \left(1 + k\, p\right) \tag{21}$$

where: $k = 0.002$ to 0.003 stands for the change of viscosity coefficient;

b) indirectly, i.e. obtaining a dynamic viscosity value by first using the Barus equation:

$$\mu = \mu_0\, e^{\alpha p} \tag{22}$$

where: $\alpha = \alpha(p, T)$ – coefficient of viscosity depending on pressure, μ_0 - value of dynamic viscosity under atmospheric pressure, and at an appropriate operating temperature (see Fig. 5).

The kinematic viscosity calculation drawn from this model is done in relation to the calculated value of dynamic viscosity and the density at the operating temperature and pressure using the following formula:

$$\nu_p = \frac{\eta_p}{\rho_p} = \frac{\mu_0\, e^{\alpha p}}{\rho_x \left(1 + \dfrac{\Delta p}{K_T}\right)} \tag{23}$$

which follows from Eqs. (14), (16) and (23).

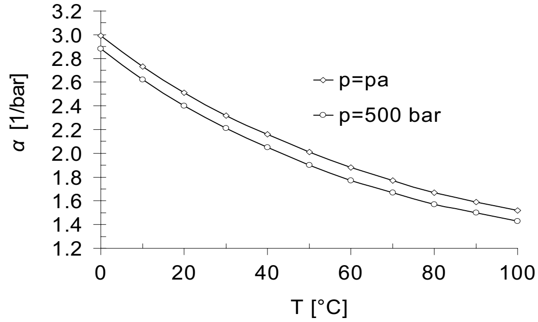

Fig. 5. *The alteration of the coefficient α as a function of any change in temperature, and operating pressure ranging from p_a to 500 bar for mineral oils with paraffin base structure [5]*

3 NUMERICAL VALIDATION OF THE PROPOSED MODEL

The correlation of temperature and pressure with changes in the key properties of fluids, which should be taken into account when calculating pressure losses within hydraulic systems, is presented in Chapters 1 and 2. It remains unclear whether change in density and viscosity substantially effects pressure loss in hydraulic systems, and whether they should be considered while designing a hydraulic system; and if so, how to set up a general model for calculating the exact loss of pressure.

It only makes sense to answer the question with regard to a representative model of the pipeline complying with defined criteria, as follows:

- pipeline diameters 15, 25 and 40 mm alternately;
- pipeline length 1 m;
- velocity of flow 6 m/s;
- type of hydraulic mineral oil HM46, viscosity index 90 to 100;
- operating temperature of the hydraulic oil 50 °C;
- density of the hydraulic oil 875 kg/m^3 at 15 °C;
- operating pressure 100, 200, 300 and 400 bar;
- the nature of the pressure change: adiabatic.

3.1 Step 1 - Calculation Model for Determining Oil Density at Operating Temperature 50 °C, and Atmospheric Pressure.

The volumetric temperature expansion coefficient equals (Fig. 2) α_p=7.0·10^{-4}, which makes the fluid density at operating temperature 50 °C and under atmospheric pressure equal to:

$$\rho_{50} = \rho_{15}\left[1-0.0007\ (T-288)\right] = 853.6\ \ \text{kg/m}^3\ .$$

3.2 Step 2 - Calculation Model for Determining Oil Density under Operating Pressure

The compression module for the adiabatic change of pressure (Fig. 3) equals:

a) p_1 = 100 bar $\Rightarrow$ K_{S1} = 17400 bar;
b) p_2 = 200 bar $\Rightarrow$ K_{S2} = 18200 bar;
c) p_3 = 300 bar $\Rightarrow$ K_{S3} = 19200 bar;
d) p_4 = 400 bar $\Rightarrow$ K_{S4} = 20500 bar.

Oil density under the defined pressures equals:

$$\rho_{100} = \rho_0\ \left(1+\frac{p_1}{K_{T1}}\right) = 858.5\ \ \text{kg/m}^3$$

$$\rho_{200} = 862.9\ \ \ \text{kg/ m}^3$$

$$\rho_{300} = 866.9\ \ \ \text{kg/m}^3$$

$$\rho_{300} = 870.3\ \ \ \text{kg/m}^3\ .$$

The density change curve as a function of operating temperature and temperature, is shown in Figure 6.

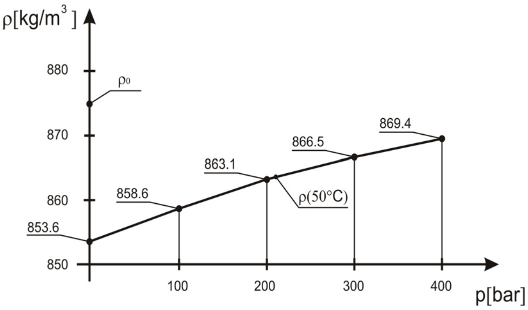

Fig. 6. *Density change as a function of pressure change at temperature 50 °C*

3.3 Step 3 - Calculation Model for Determining Viscosity at Operating Temperature

Kinematic viscosity of oil HM 46 is 46·10^{-6} m^2/s at 40 °C and 30·10^{-6} m^2/s at 50 °C.

3.4 Step 4 - Calculation Model for Determining Viscosity under Operating Pressures

Kinematic viscosity at 50°C and under atmospheric pressure equals 25·10^{-6} m^2/s, whereas pressure coefficient is 0.0025. Therefore, viscosity of the determinate operating pressures equals:

- p_1 = 100 bar:
  $\nu_{100} = \nu\ (1+k\cdot\ p_1) = 37.5\cdot 10^{-6}\,\text{m/s}^2$;
- p_2 = 200 bar; $\nu_{200} = 45\cdot 10^{-6}\,\text{m/s}^2$;
- p_3 = 300 bar; $\nu_{300} = 52.5\cdot 10^{-6}\,\text{m/s}^2$;
- p_4 = 400 bar; $\nu_{400} = 60\cdot 10^{-6}\,\text{m/s}^2$.

3.5 Step 5 - Calculation Model for Determining Pressure Loss

a) Viscosity corrected in accordance with the level of operating temperature. The starting parameters:
   ν_{50} = 30·10^{-6} m^2/s; ρ = 875 kg/m^3;
   v = 6 m/s; d = 25 mm; L = 1 m.
b) Viscosity corrected in accordance with the level of operating temperature and operating pressure. The starting values:
   v = 6 m/s; d = 25 and 15 mm; L = 1 m.

- $p_a \Rightarrow \nu_0$ = 30·10^{-6} m^2/s; ρ_0 = 875 kg/m^3;
- p_1 = 100 bar $\Rightarrow$ ν_{100} = 37.5·10^{-6} m^2/s;
  ρ_{100} = 858.5 kg/m^3;
- p_2 = 200 bar $\Rightarrow$ ν_{200} = 45·10^{-6} m^2/s;
  ρ_{200} = 862.9 kg/m^3;
- p_3 = 300 bar $\Rightarrow$ ν_{300} = 52.5·10^{-6} m^2/s;
  ρ_{300} = 866.5 kg/m^3;
- p_4 = 400 bar $\Rightarrow$ ν_{300} = 60·10^{-6} m^2/s;
  ρ_{400} = 870.3 kg/m^3.

An example of the calculation model for determining turbulent flow: step 5a

- The Reynolds number equals:
  $Re = \dfrac{v\ d}{\nu} = 5000\ .$
- The friction coefficient equals:
  $\lambda = \dfrac{0.3164}{Re^{0.25}} = 0.0376\ .$

- The pressure decrease within tube network equals:

$$\Delta p = \lambda \ \frac{L}{d} \ \frac{v^2}{2} \ \rho = 23686 \ \text{ Pa} .$$

An example of the calculation model for determining the flow during the liminal phase: step 5b

$$Re = \frac{v\, d}{\nu} = 3000$$

$$\lambda = 3.9 \cdot 10^{-6} \cdot Re + 0.0242 = 0.0359 .$$

$$\Delta p = \lambda \ \frac{L}{d} \ \frac{v^2}{2} \ \rho = 36435 \ \text{ Pa} .$$

An example of the calculation model for determining laminar flow: step 5c

$$\mathrm{Re} = \frac{v\, d}{\nu} = 1500$$

$$\lambda = \frac{64}{\mathrm{Re}} = 0.0427.$$

$$\Delta p = \lambda \ \frac{L}{d} \ \frac{v^2}{2} \ \rho = 44548 \ \text{ Pa} .$$

Summary of the overall calculation for both pipe diameters is shown in in Figure 7.

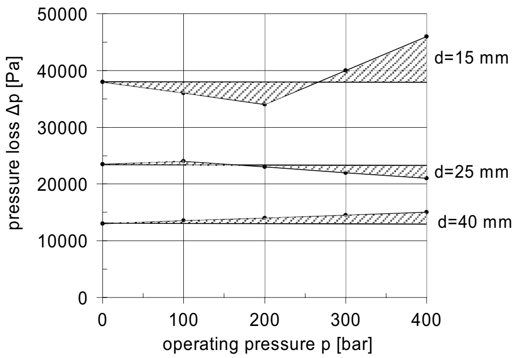

Fig. 7. *Pressure loss as a function of the operating pressure level and the pipe diameter*

4 CONCLUSIONS

Generally accepted methods for calculating pressure losses within flat pipelines, as presented in technical literature and used in praxis are based on the Reynolds number, which considers viscosity and density of fluid, internal pipe friction coefficient, pipe geometry, and oil circulation speed.

Technical literature treats the aspect of density and viscosity alteration as a function of temperature, and pressure change as an isolated issue with only tangential links to the problems of designing and calculating a hydraulic system. Nominal values for viscosity (at 40 °C) and density (at 15 °C and normal atmospheric pressure), which differ substantially from real conditions, are considered. Consequently, the derived values cannot be regarded as highly accurate, leading to inaccurate calculation of pressure losses (in some cases up to 200%).

The numerical model, which takes into account the actual changes of density and viscosity at the current oil pressure and temperature in order to overcome the above weakness, is suggested in this paper. Such an approach is novel and provides a new capacity for an accurate pressure drop analysis of advanced hydraulic systems.

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