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THEORETICAL APROACH REGARDING FLUID FLOW WITHIN ORIFICES OF CONSTANT SECTION

Abstract: *In the working circuit of a hydro-static drive system, the working fluid is the support on which energy transmission is based between the energy source and the actuated work-piece. In order to accomplish this, the fluid is circulated between the primary components via the circuit piping. The working fluid flow through the pipelines forming the system circuit represents a complex phenomenon influenced by a series of changes specific to both the fluid medium and the parameters at which the flow is accomplished represented by the working pressure, circulation velocity or temperature values within the system. The change of these flow parameters is also made due to the ducts and orifices type through which the fluid is forced to pass, resulting in a specific pressure drop due to the inertial forces and fluid viscosity. In this paper are presented theoretical aspects regarding fluid flow through orifices of constant section, as well as the numerical analysis performed on the virtual model for highlighting the specific flow parameters. The obtained results are presented in terms of total pressure, fluid velocity and turbulences registered at the analyzed fluid region being emphasized the fluid stream contraction during the orifice passage and the fluid trend afterwards along the pipeline axis.*

Key words: *fluid flow, circular orifices, pressure drop, three-dimensional model, numerical analysis.*

INTRODUCTION

The sustained development of hydro-static techniques used on a great variety of machines in the industrial branches was possible due to the continuous design improvements made on the actuating components being responsible for carrying out many difficult tasks from a variety of working domains.

The working principle of hydrostatic systems is mainly based on the same classical method of transmitting energy between primary components by means of an incompressible fluid.

The working fluid flow between the primary components of a hydraulic installation represents a complex phenomenon which is always characterized by energy losses mainly due to the flow regime but also to the flowing section geometry that undergoes continuous changes due to repeated passage through various devices in use that are using different diameter connections.

Thus it is necessary to know and detail the fluid mechanics principles whose equations are applicable to describe the flow phenomenon in order to characterize the situations occurring in the hydrostatic drive systems installations.

There are presented aspects regarding the fluid flow through the hydraulic circuit pipelines, but also through orifices of constant section, which are capable to determine specific flow resistances to the working fluid during system operation.

In order to highlight the flow parameters, a numerical fluid flow analysis is performed on the virtual duct model containing a constant section orifice that introduces a change in the flow section to the working fluid path.

The values of total pressure, fluid velocity, as well as turbulences recorded inside the analyzed flow region are highlighted [5].

2. FLUID MECHANICS PRINCIPLES FOR FLOW WITHIN HYDRAULIC WORKING CIRCUIT

The movement of a fluid particle through the hydrostatic drive duct lines is a phenomenon that can be defined with a number of seven parameters referring to the coordinates of its mass center with respect to the chosen coordinate system (x, y, z), the system pressure, working temperature, density and viscosity of the fluid.

It is necessary to formulate seven independent equations to make possible to express each parameter according to time.

For the coordinates of the mass center in relation to the reference system (the first three equations of motion) the Navier-Stokes equations are used for the laminar flow, while for the turbulent flow regime the Reynolds system is used.

From the law of the fluid mass conservation results the fourth equation and represents the fluid flow continuity equation, the fifth equation derives from the law of energy conservation or the first principle of thermodynamics and the last equations result from the equation of state and the viscosity variation law with pressure and temperature.

For studying the stationary or transient flow regime of the working fluid through the hydrostatic circuit, the continuity equation or the Bernoulli equation applied for the case of introducing the hydraulic resistances in the circuit are used.

These resistors in the flow path are given by the various devices that are attached to the circuit but also from the transport components represented by the pipes, armatures, elbows, branches, which affect the fluid flow and implicitly the overall efficiency of the system. For such components, specific relationships are used for hydraulic load losses during circuit operation [2], [3].

3. FLUID FLOW THROUGH CIRCULAR DUCTS OF THE HYDRAULIC CIRCUIT

It is known that the working fluid flow pattern in the hydrostatic drive circuit is influenced by the laminar or turbulent flow regime.

For the laminar flow regime is considered a high value of fluid kinematic viscosity, the flow is accomplished through pipes of low nominal diameter value and the flow velocity is ranged below a permissible limit value which for mineral oil is maximum 12 m/s.

Higher flow velocities values are recorded at the pipe axis while for the region near the walls velocity values are lower due to the fluid wall adhesion (parabolic or Hagen-Poiseuille velocity values distribution).

Thus, fluid flow through the circuit pipelines is characterized by load losses or pressure drops due to fluid inertial and viscosity forces described by Darcy's relationship written for two points along the pipeline [4]:

$$\Delta_p = p_1 - p_2 = \lambda \frac{\rho}{2} \cdot \frac{l}{d} \cdot \omega_{med}^2 \quad (1)$$

where:

λ - coefficient of linear loss;

ρ - fluid density;

l, d – pipeline length and diameter;

ω_{med} - average flow velocity.

These pressure losses must be compensated by the circuit drive pump and are summed up to the pressure required to operate the hydraulic motor.

The linear loss coefficient describes the load losses magnitude for system operation having values for both isothermal and non-isothermal laminar flow types ranging from [4]:

$$\frac{64}{\text{Re}} \le \lambda \le \frac{75}{\text{Re}} \quad (2)$$

Laminar flow occurs up to the Reynolds limit number whose values are up to Re = 2320 for liquids in general and Re = 2000 for mineral oil.

Above these values of the Reynolds number, the flow is turbulent, the laminar layer becomes disordered, the thickness of the turbulent layer rising towards the centre of the pipeline.

In this case the coefficient of linear loss depends on:
- Reynolds number;
- the roughness of the pipe walls;
- temperature;
- circuit geometry.

The coefficient of linear loss is evaluated with the relations [4]:

a) Blassius:

$$\lambda = \frac{0.3164}{\sqrt[4]{\text{Re}}} \quad for \;\; 4 \cdot 10^3 < \text{Re} < 10^5 \quad (3)$$

b) Prandtl-Karman:

$$\frac{1}{\lambda} = \frac{2}{\rho \cdot \text{Re}\sqrt{\lambda} - 0.8} \quad for \;\; 3 \cdot 10^3 < \text{Re} < 10^7 \quad (4)$$

4. FLUID FLOW THROUGH CIRCULAR ORIFICES OF CONSTANT SECTION

In the practice of hydraulic drives, different devices are used which, by construction, have orifices of different diameters through which the working fluid must circulate in order to achieve a certain specific function.

The case of the fluid flow through a constant section circular orifice of sharp edges is presented and schematically shown in figure 1.

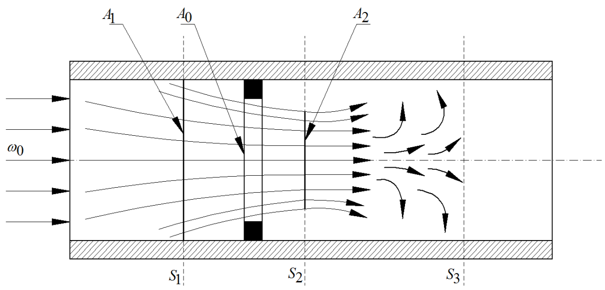


Fig. 1 The schematically representation of fluid flow through circular orifices of constant section.

Sections S1, S2 and S3 are considered, between which the fluid flow is evaluated as follows:
- between the sections S1 and S2 the fluid is accelerated in a potential movement that occurs with small energy losses;
- in the orifice area the fluid flow is contracted so that the area of the contracted current section is smaller than the section of the orifice;
- between sections S2 and S3 the flow regime is strongly turbulent.

In order to determine the characteristic of the circular orifice of constant section between the fluid sections S1 and S2, Bernoulli's equation is written [1]:

$$\frac{\alpha_1 \omega_1^2}{2g} + \frac{p_1}{\rho g} = \frac{\alpha_2 \omega_2^2}{2g} + \frac{p_2}{\rho g} + \xi \cdot \frac{\omega_2^2}{2g} \quad (5)$$

where:

α_1, α_2 - Coriolis coefficients;

ξ - load loss coefficient.

In the contracted current region there is a difference between the flow sections and the ratio of the two flow areas is given by the contraction coefficient as follows [1]:

$$C_c = \frac{A_2}{A_0} \quad (6)$$

Considering the flow continuity equation between the three sections (figure 1) can be assumed [1]:

$$A_1\omega_1 = A_2\omega_2$$
$$\omega_1 = \omega_2 \cdot \frac{A_2}{A_1} = C_c \cdot \omega_2 \cdot \frac{A_0}{A_1} \quad (7)$$

The average velocity in the contracted fluid section can be calculated using the following relationship if the Coriolis coefficients are considered of unitary value [1]:

$$\omega_2 = \frac{1}{\sqrt{1+\xi - C_c^2 \cdot \frac{A_0^2}{A_1^2}}} \cdot \sqrt{\frac{2(p_1 - p_2)}{\rho}} \tag{8}$$

The first term of equation (8) is the velocity coefficient, and the second is the theoretical velocity of the fluid flow in section S2.

The steady state orifice characteristic can be written as follows [1]:

$$Q = C_d \cdot A_0 \cdot \sqrt{\frac{2(p_1 - p_2)}{\rho}} = C_d \cdot A_0 \cdot \omega_2 \tag{9}$$

where:

C_d - fluid flow rate coefficient.

$$C_d = C_c \cdot C_v \tag{10}$$

The stationary orifice characteristic can be also calculated using the equivalent relationship [1]:

$$\frac{p_1 - p_2}{\rho g} = \xi \cdot \frac{\omega_0^2}{2g} = \xi \cdot \frac{Q^2}{2gA_0^2}$$
$$\xi = \frac{1}{C_d^2} \tag{11}$$

The load loss on the considered orifice is calculated by taking into account the overall loss coefficient as follows [1]:

$$\Delta p = p_1 - p_2 = \xi \cdot \frac{\rho}{2} \cdot \frac{Q^2}{A_0^2} \tag{12}$$

Thus, the pressure drop can be calculated as a result of the fluid flow through the constant sectional orifice depending on the fluid flow rate, (Q), the orifice area, (A_0), the fluid density, (ρ), when the value of the overall load loss coefficient (ξ) is known.

5. FLUID FLOW NUMERICAL ANALYSIS

In order to be able to highlight the flow parameters of the working fluid through an orifice of constant section, a numerical analysis was performed on a virtual model. The model is designed for a circular duct with an inner orifice of constant section.

The fluid region is declared inside the three-dimensional model made with the Solid Edge V20 program, the working fluid being a mineral oil with a density of 900 kg/m3 and viscosity of 32 cSt.

The overall dimensions of the model are 100 mm long, 50 mm outer diameter, 33.4 mm inner diameter, 25 mm orifice diameter, 5 mm orifice width.

Flow analysis is performed using the ANSYS CFX program.

The main analysis domains represented by the solid domain and the fluid region located inside of the duct are shown in Figure 2.

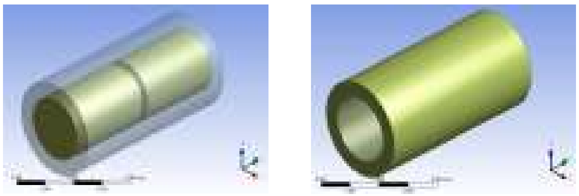


Fig. 2 The main analysis domains

For the mesh network, the triangular element option was chosen, being obtained a number of 16857 nodes and 82541 elements for the analyzed model (figure 3).

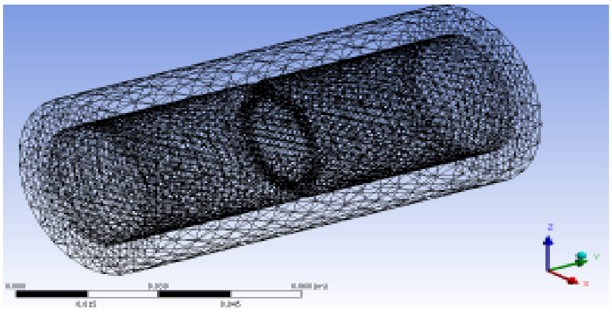
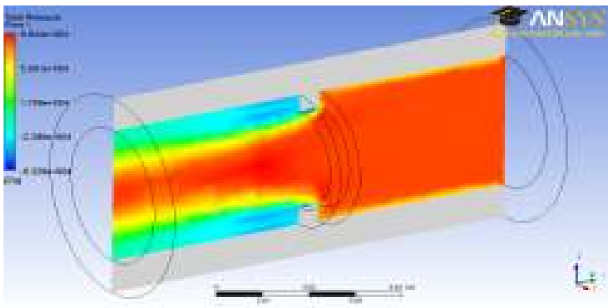


Fig. 3 The mesh network

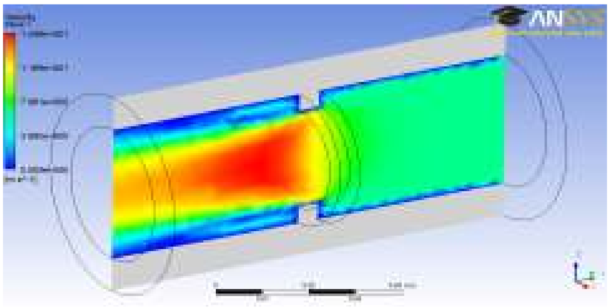
The working fluid flow is analyzed between the pipe inlet and outlet with passage through the inner orifice of the reduced diameter and constant section.

A fluid flow velocity of 7 m/s is declared at the pipe inlet, corresponding to a velocity used inside hydro-static circuits. Changes in the velocity and pressure values at the fluid region level containing the inner orifice of constant section as well as high turbulence values at the orifice outlet port are expected.

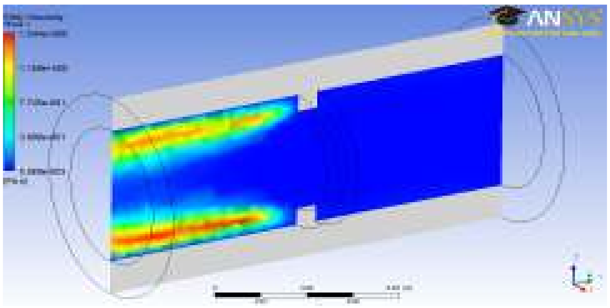
The results obtained are shown in Figure 4.



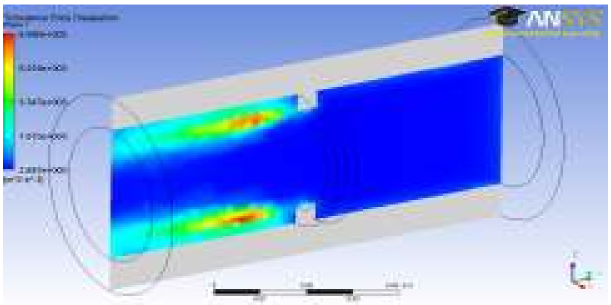
a) Total pressure values



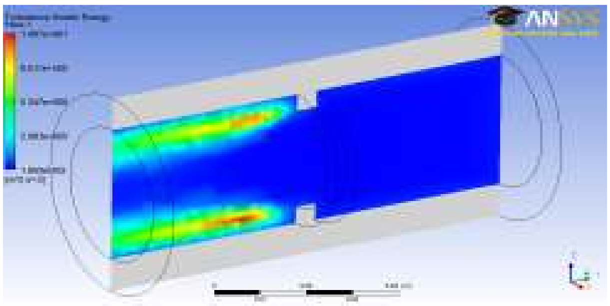
b) Fluid velocity values



c) Eddy viscosity values



d) Turbulence eddy dissipation values



e) Turbulence kinetic energy values

Fig. 4 The numerical analysis results.

Analyzing the obtained results it can be seen the specific values for the total pressure and the flow velocity of the fluid inside the pipe following the path lines at the passage through the constant section orifice. High turbulent values are also recorded when passing through the inner orifice inside the pipeline.

It can be seen on the obtained results the image of the fluid flow stream which is contracted at the inner orifice inlet so that the effective flow section area is smaller than the orifice opening area.

Thus, the theoretical aspects previously described regarding fluid flow through inner orifice of constant section are verified.

6. CONCLUSIONS

Hydrostatic drive systems are used in most industrial branches today. These systems perform the power transmission between the primary elements of the circuit by means of a working fluid. Fluid flow inside the working circuit occurs according to the fluid mechanics laws applied for flowing through pipes or orifices of constant or variable section. During the operation important stresses are recorded acting on the working fluid due to system high pressure values inside the circuit but also to the fluid lamination while is conveyed through small diameter orifices and ducts.

In this paper were described theoretical aspects regarding the fluid mechanics principles and the flow regime of the working fluid inside pipes and circular orifices of constant section, parts of the hydrostatic drive circuit. A numerical flow analysis of the working fluid on a virtual model was made in order to illustrate the flow pattern through a circular orifice of constant section.

On the numerical obtained results are highlighted the values for the fluid velocity circulation recorded locally on the analyzed model, the total pressure values, but also the values of the specific turbulences that inevitably occur when flow section change at the inner orifice level inside the pipeline.

The phenomenon of fluid stream contraction is observed on the flow path lines as a result of the fluid crossing through the constant section orifice, the contracted stream section being kept even after the fluid pass over the orifice section and moves forward along the pipeline axis.

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