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Analysis of Oil Leaks in a Variable-Height Gap Between the Cylinder Block and the Valve Plate in a Piston Pump by Means of Author-Designed Software and CFD Fluent

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Summary. The paper presents computational models for obtaining oil leaks intensity in a variable height gap between the cylinder block and the valve plate in an axial piton pump. The computations are based on numerical methods and commercially available software CFD Fluent. By means of the models developed analysis of leak flow intensity is performed for variable parameters and dimensions of the pump.
Key words: oil leaks, gap between the cylinder block and valve plate, piston pump.

INTRODUCTION

Piston pumps are applied in the drives of complex machines with high demands concerning efficiency and reliability. This provides an incentive for continuous development towards improving exploitation parameters of those machines by modernizing their construction [8, 9, 17] The range of applications of piston pumps is wide and still expanding. Examples of devices employing piston pumps are presented in Fig. 1 [7, 14, 15, 16].

The most important applications of hydraulic piston machines include:
- aviation industry (airplanes);
- automotive industry (presses, machining centres, injection molding machines);
- heavy industry (pressure foundries, rolling mills, cokeries);
- construction industry (excavators, loaders, extension arms);
- foresting and agriculture machines (cranes, elevators, drilling rigs, harvesters);
- military vehicles (multi-function vehicles, vehicles used for constructing bridges).

The biggest manufacturers include such companies as Parker and Bosch-Rexroth.

In piston pumps energy losses occur at the mating surfaces: piston-cylinder, slipper-swash plate and cylinder block-valve plate. The latter forms the valve system, an important part of every hydraulic pump, which deserves special attention in examining the characteristics of hydraulic machines.

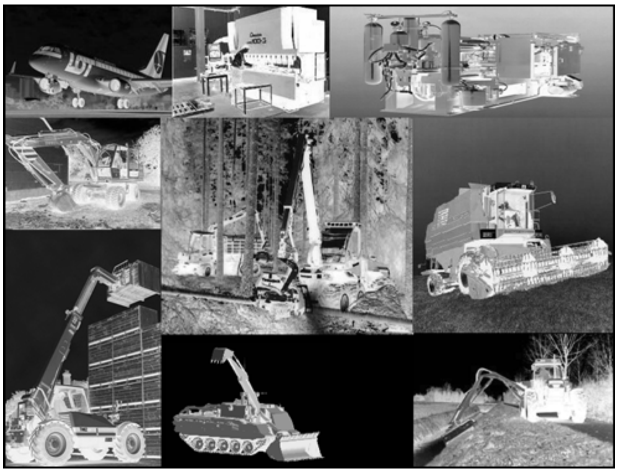

Fig. 1. Applications of piston pumps

In real conditions, the gap between the cylinder block and the valve plate is of variable height due to differences in torques coming from hydrostatic pressing and relieving forces which affect the position of the cylinder block [1, 2, 3, 4, 11, 12, 13, 18].

When a pump is operating, oil leaks to the outside and inside of the valve plate affecting the volumetric efficiency of the pump and its other parameters.

The paper employs numerical methods and a computational model developed within the software package CFD Fluent for determining oil leaks intensity in the valve system of an axial piston pump.

COMPUTATION MODEL OF OIL FLOW INTENSITY IN THE GAP BETWEEN THE CYLINDER BLOCK AND VALVE PLATE

To determine oil flow intensity in the gap between the cylinder block and valve plate, a numerical model was developed [18]. The following assumptions were adopted in the model [5, 10]:

– the flow is laminar;
– surfaces are infinitely rigid;
– the liquid completely fills the gap;
– tangent stress is Newtonian;
– the liquid is incompressible;
– inertia forces of the liquid are negligible.

Besides, cavitation and heat transfer phenomena were disregarded.

In the model developed, the valve plate was divided into four zones of oil leak flow, namely the discharge port, the inlet port, the upper transition zone and the lower transition zone. In all the four zones oil leaks occur to the inside and outside of the valve plate. In the transition zones, there are also leaks between the discharge and inlet zones.

In the transition zones, the oil leak intensity was obtained from the elementary product of the variable-height gap and the mean flow velocity as in the formula below:

$$Q = P\frac{1}{n}\sum_{i=0}^{n}(\upsilon_r)_{sr\,i} \tag{1}$$

where:
P – total cross-section area of the gap,
n – number of interpolation intervals,
$(\upsilon_r)_{sri}$ – mean flow velocity.

The flow cross-section was obtained on the basis of the numerical integration by trapezoidal rule, according to [6]:

$$P = l_n\left[\frac{h(r,\varphi_0)+h(r,\varphi_n)}{2}+\sum_{i=1}^{n-1}h(r,\varphi_i)\right] \tag{2}$$

where:
$h(r, \phi)$ – height of the variable-height gap at the radius and angle under consideration;
ϕ_0 – angle at the entry of the zone under consideration,
ϕ_n – angle at the exit of the zone under consideration,
n – number of intervals in the numerical integration by trapezoidal rule,
l_n – length of the interval in the numerical integration.

The gap height in a given interval was obtained from

$$h = -r\sin\varphi\cdot\cos\delta\cdot tg\varepsilon - r\cos\varphi\cdot\sin\delta\cdot tg\varepsilon + Rtg\varepsilon + h_1 \tag{3}$$

where
r – current radius of a given cross-section,
ϕ- angle of a given flow cross-section,
ε – inclination angle of the cylinder block,
δ – angle between the axis x and the smallest gap height h_1,
R – radius of the cylinder block.

The computation model of the oil leak intensity was implemented in the programming language C++ with the use of the VCL library. The software so developed makes it possible to analyse the leak flow intensity in a variable-height front gap in the valve system of different construction variants of a piston pump. The software also enables the user to set the accuracy of computations by prescribing the number n of interpolation intervals. Thanks to using the VCL library, it is possible to represent the results visually in the form of graphs and to save them as text files.

The total leak flow intensity in the valve system is obtained by adding the leaks from the particular flow zones.

COMPUTATION MODEL OF OIL LEAK FLOW INTENSITY EMPLOYING CFD FLUENT

An alternative method of examining oil leak flow intensity in the gap between the cylinder block and valve plate was developed on the basis of commercially available software CFD Fluent. The stages of building the model of the variable-height gap in the CFD Fluent package are presented in Fig. 2.

The geometrical model of the variable-height gap was constructed in the Auto-Cad programme for two construction types of the valve plate: with positive overlap and with relief grooves (Fig.3). In both cases, the same dimensions of the radius were applied $r_1 = 0.0284$ m, $r_2 = 0.0304$ m, $r_3 = 0.0356$ m and $r_4 = 0.0376$ m respectively, and the same length of the transition zones α_m, equal to 45[°].

A numerical grid generated automatically in the programme Gambit was then implemented on the geometrical model of the variable-height gap. The grid consists of volumetric cells of the Hex/Wedge type suitable for the gap shape. Besides, the regions of boundary conditions were specified in the programme Gambit (Fig.4).

The last stage of constructing the numerical model of the variable-height gap in the valve system is to enter the numerical grid with the boundary condition regions to the programme Fluent, in which the values of oil pressure in the boundary regions are determined and simulations of oil pressure distribution are performed. On the basis of the so obtained pressure area on the inside and outside of the valve plate, the oil leak flow intensity is determined.

Fig. 2. Stages of building the model of the variable-height gap in the CFD Fluent package

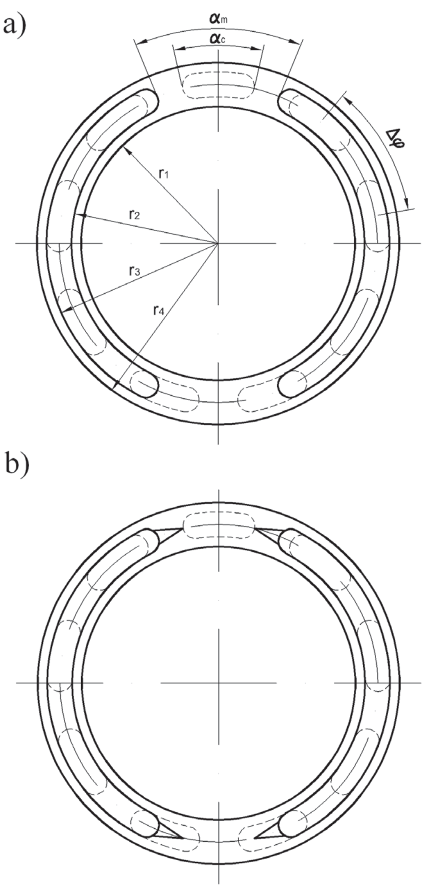

Fig. 3. Construction variants of the valve plate a) with positive overlap b) with relief grooves

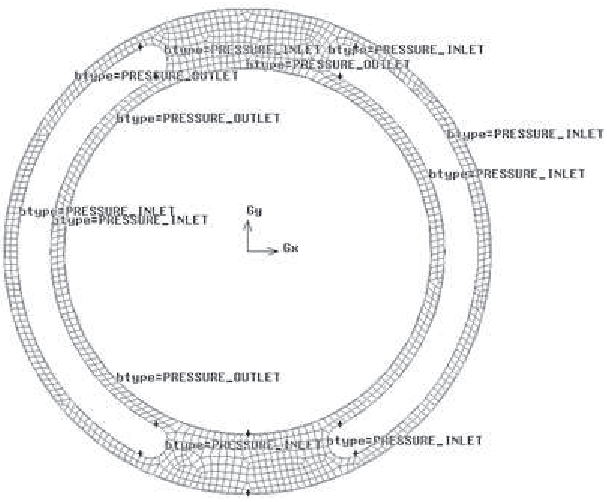

Fig. 4. Numerical grid consisting of volumetric cells of the Hex/Wedge type and boundary condition region

RESULTS OF COMPUTATIONS

The computational models developed and described above were applied for determining the total oil leak flow intensity in the gap between the cylinder block and valve plate in a hydraulic piston pump. The analysis was performed for variable dimensions and exploitation parameters such as the discharge pressure p_t, the angular velocity ω of the cylinder block, the dynamic viscosity η of oil and the angle ε of the cylinder block inclination for two constructional variants of the valve plate: the positive overlap variant and the relief groove variant.

The following input data were assumed in the computational model:

- in the pressure port the discharge pressure p_t = 32 MPa,
- in the suction port the inlet pressure p_s = 0.1 MPa,
- outside and inside the valve plate the pressure p_o = 0 MPa,
- angular velocity ω of the cylinder block ω = 157 rad/s,
- oil dynamic viscosity coefficient η = 0.0258 Pas,
- angle δ = 0.785 rad between the axis x and the smallest gap height h_1,
- angle between the cylinder block and valve plate ε = 0.000523 rad,
- minimal gap height $h_1 = 2\cdot10^{-6}$m,
- characteristic radiuses of the valve plate in a given pump are r_1 = 0.0284 m, r_2 = 0.0304 m, r_3 = 0.0356 m and r_4 = 0.0376 m.

Fig. 5 presents the variation of the oil leak flow intensity as a function of the discharge pressure p_t.

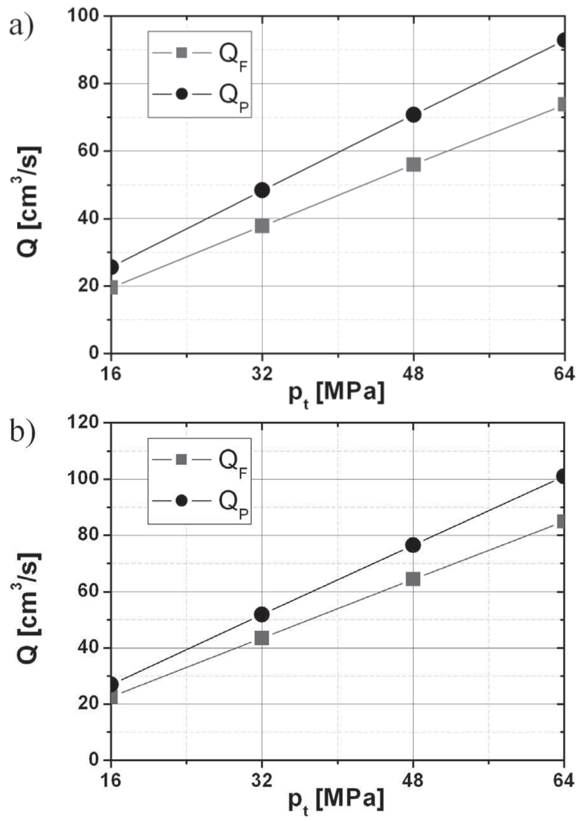

Fig. 5. Total oil leak flow intensity in the valve system as a function of the discharge pressure p_t obtained by means of the programme Q_P developed by the authors and CFD Fluent Q_F a) positive overlap valve plate, b) valve plate with relief grooves

Increase in the discharge pressure causes linear increase in the leak flow intensity.

Fig. 6 presents the variation of the oil leak flow intensity as a function of the angular velocity ω of the cylinder block.

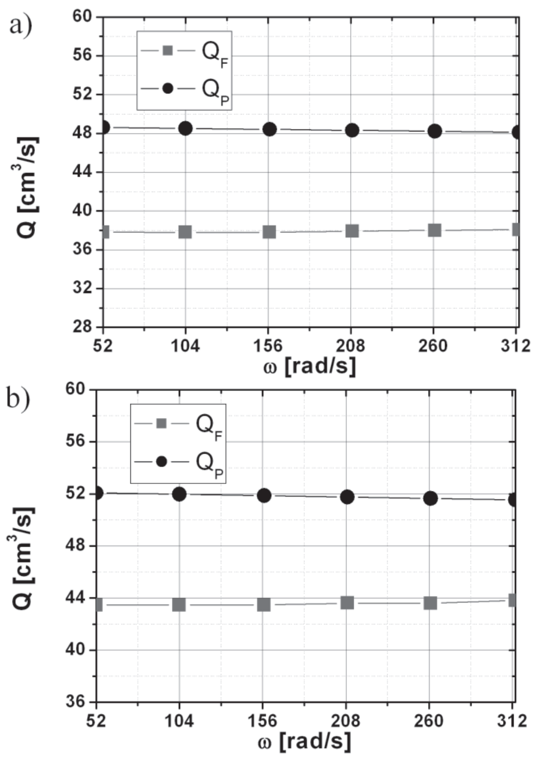

Fig. 6. Total oil leak flow intensity in the valve system as a function of the angular velocity ω of the cylinder block obtained by means of the programme Q_P developed by the authors and CFD Fluent Q_F a) positive overlap valve plate, b) valve plate with relief grooves

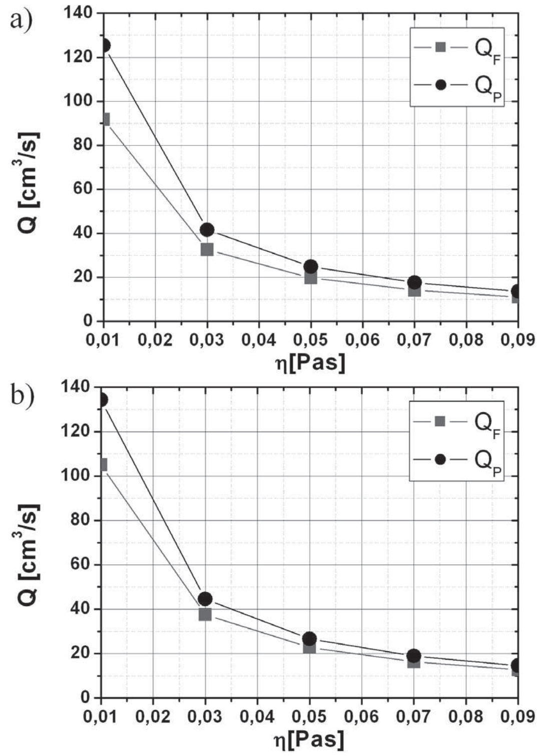

Fig. 7. Total oil leak flow intensity in the valve system as a function of the dynamic viscosity η of oil obtained by means of the programme Q_P developed by the authors and CFD Fluent Q_F a) positive overlap valve plate, b) valve plate with relief grooves

Increase in the angular velocity of the cylinder block does not significantly affect the leak flow intensity.

Fig.7 presents the variation of the oil leak flow intensity as a function of the dynamic viscosity coefficient η of oil.

Increase in the dynamic viscosity of oil causes decrease in the oil leak flow intensity in the valve system.

Fig. 8 presents the variation of the oil leak flow intensity as a function of the angle ε of the cylinder block inclination obtained by means of the programme developed by the authors and by means of CFD Fluent.

It can be observed that increase in the inclination angle of the cylinder block leads to a significant increase in the intensity of leak flow in the valve system.

Having obtained the results of oil leak flow intensity from the two sources, i.e. the programme developed by the authors and from CFD Fluent, we went on to compare them. The comparison was made by calculating relative differences (4) between the results of oil leak flow intensity obtained from Q_P and from CFD Fluent Q_F. The relative differences were calculated according to:

$$\delta_Q = \frac{|Q_P - Q_F|}{|Q_F|} \cdot 100\% \,, \quad (4)$$

Table 1 presents selected relative differences between the results obtained from the two sources, i.e. the authors' programme and CFD Fluent for the variable angle ε of the cylinder block inclination.

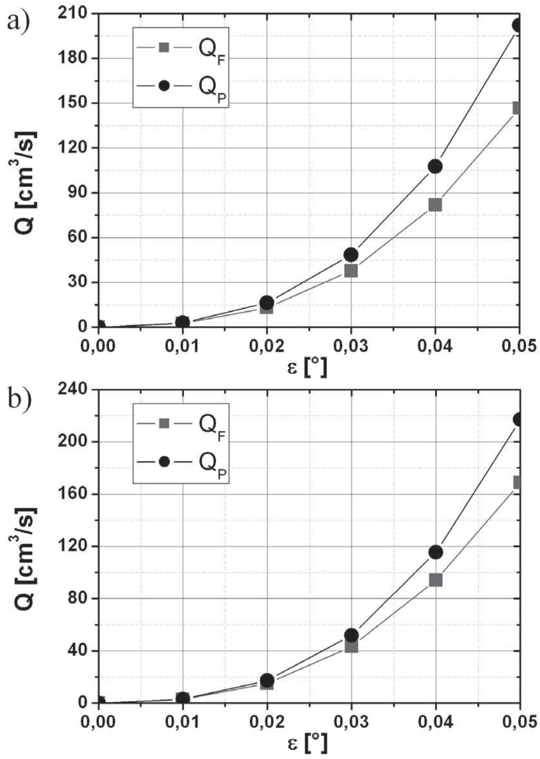

Fig. 8. Total oil leak flow intensity in the valve system as a function of the angle ε at which the cylinder block is inclined obtained by means of the programme Q_P developed by the authors and CFD Fluent Q_F a) positive overlap valve plate, b) valve plate with relief grooves

Table 1. Relative differences δ_Q between the values of total leak flow intensities obtained from the authors' programme and from CFD Fluent depending on the angle ε of the cylinder block inclination for the two variants of the valve plate

ε [°]	Positive overlap	Relief grooves
	δ_Q [%]	δ_Q [%]
0	6,43	3,83
0,01	17,53	10,4
0,0 2	24,25	15,68
0,03	28,1	19,31
0,04	31,52	22,69
0,05	37,88	28,68

As can be seen, the values of the relative differences between the results obtained from the authors' programme and from CFD Fluent increase with the increase in the angle ε of the cylinder block inclination. In the case of a positive overlap valve the increase is from 6% to about 38% and in the case of a valve with relief grooves the difference groes from about 4% to about 29%.

CONCLUSIONS

The study can be concluded by the following observations:

1. The models developed provide adequate tools for determining the flow intensity of oil leaks depending on the variable parameters and dimensions of the pump.
2. Increase in the cylinder block inclination angle and in the discharge pressure cause increase in the intensity of oil leak flow. Increase in the dynamic viscosity contributes to decrease in the intensity of leak flow and increase in the angular velocity of the cylinder block does not significantly affect it.
3. The intensity of oil leaks is greater for a valve plate with relief grooves than for a positive overlap valve plate.

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ANALIZA PRZECIEKÓW OLEJU W SZCZELINIE ROZRZĄDU POMPY WIELOTŁOCZKOWEJ Z UWZGLĘDNIENIEM WŁASNEGO PROGRAMU I CFD FLUENT

Streszczenie. W pracy przedstawiono modele obliczeniowe do określania natężenia przepływu przecieków oleju w szczelinie o zmiennej wysokości pomiędzy blokiem cylindrowym i tarczą rozdzielacza pompy wielotłoczkowej. W obliczeniach wykorzystano metody numeryczne oraz komercyjny program CFD Fluent. Stosując opracowane modele przeprowadzono analizę natężenia przepływu przecieków dla zmiennych parametrów geometryczno-eksploatacyjnych pompy.
Słowa kluczowe: przecieki oleju, szczelina pomiędzy blokiem cylindrowym i tarczą rozdzielacza, pompa tłokowa.