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Oil pressure distribution in conical ring gaps

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S u m m a r y. The paper deals with oil flow in ring gaps in piston pumps and hydraulic motors. On the basis of the Navier-Stokes equations a formula describing the pressure in the gap has been established. The pressure distribution obtained for confusor and diffuser gaps were presented as functions of oil viscosity and the relative velocity of the piston for its various eccentric positions.

K e y w o r d s: piston-cylinder of a pump, ring gap, pressure distribution.

INTRODUCTION

In hydraulic systems there are gaps between adjacent surfaces [1, 2, 4, 5, 21]. The right functioning of modern hydraulic systems largely depends on complex processes occurring in such gaps. Therefore, one of the most promising developments of research on hydraulic machines and devices concerns optimization of phenomena occurring in gaps, ultimately leading to prolonging the life and increasing the reliability of these machines. Awareness of gap oil parameters, including pressure distribution, is useful for the designers of hydraulic systems [6, 8, 9, 11, 13, 14, 17, 15, 18].

Generally, what is understood as a gap is an oil-filled space between two adjacent surfaces in hydraulic machines. The gap height, i.e. the distance between the surfaces, is usually about a few micrometers. Depending on the shape of the adjacent elements, gaps can also take different shapes.

One of the most typical kinds of gaps is a ring gap occurring, among others, between the piston and cylinder in a piston pump. A fundamental classification of ring

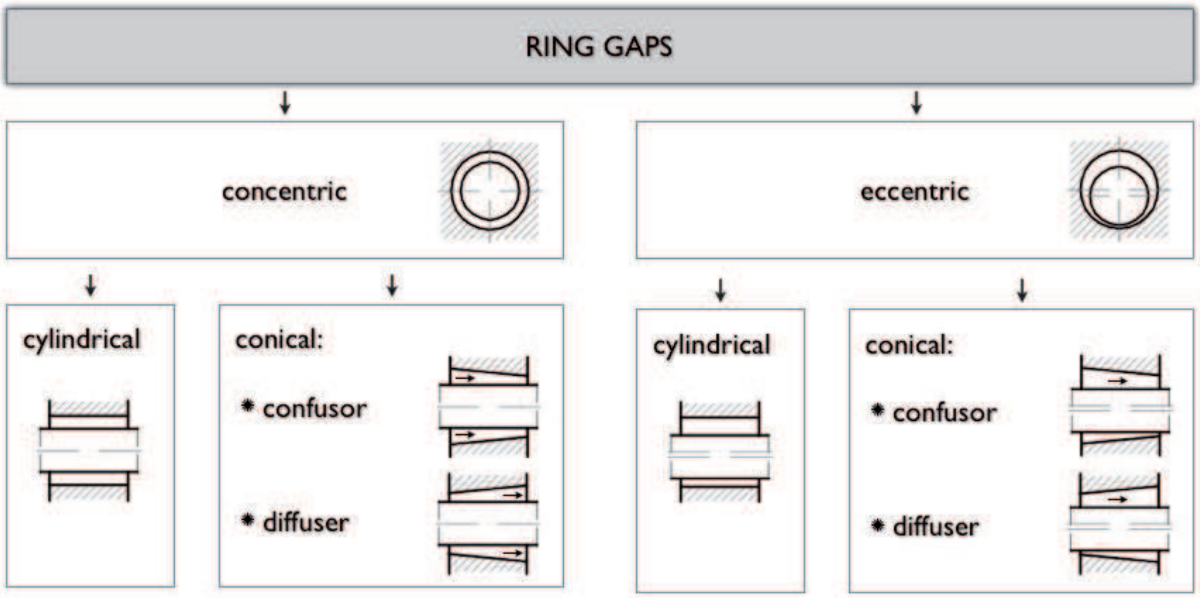

Fig. 1. Classification of ring gaps

gaps is presented in Fig. 1. A concentric gap, in which the piston axis coincides with the cylinder axis exist only in theory. In practice, the gap height varies along the cylinder due to such factors as weight, inaccuracy of manufacturing, or load asymmetry of the surfaces [16].

In this paper pressure distribution in conical gaps will be discussed. The oil may flow towards the narrower end of the gap, i.e. a confusor gap, or towards the wider end of the gap, i.e. a diffuser gap [19, 22].

All gaps, including ring ones, are a source of volumetric loss, and the leakage can occur due to pressure flow, resulting from the difference between the pressures at the gap ends, due to friction flow, resulting from the piston motion, or due to pressure-friction flow resulting from the motion of the piston and the pressure difference at the gap ends [10].

APPLICATION OF THE NAVIER-STOKES EQUATIONS FOR DETERMINING PRESSURE DISTRIBUTION IN THE GAP

The fluid motion in a ring gap can be described by means of the Navier-Stokes equations, and the continuity equation expressed in terms of the cylindrical coordinate system r, φ, z [7, 12]:

$$\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\varphi}{r}\frac{\partial v_r}{\partial \varphi}+v_z\frac{\partial v_r}{\partial z}-\frac{v_\varphi^2}{r}=$$
$$=F_r+\nu\left(\frac{\partial^2 v_r}{\partial r^2}+\frac{1}{r}\frac{\partial v_r}{\partial r}+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial \varphi^2}+\frac{\partial^2 v_r}{\partial z^2}-\frac{v_r}{r^2}-\frac{2}{r^2}\frac{\partial v_\varphi}{\partial \varphi}\right)-\frac{1}{\rho}\frac{\partial p}{\partial r},\quad(1)$$

$$\frac{\partial v_\varphi}{\partial t}+v_r\frac{\partial v_\varphi}{\partial r}+\frac{v_\varphi}{r}\frac{\partial v_\varphi}{\partial \varphi}+v_z\frac{\partial v_\varphi}{\partial z}+\frac{2v_r v_\varphi}{r}=$$
$$=F_\varphi+\nu\left(\frac{\partial^2 v_\varphi}{\partial r^2}+\frac{1}{r}\frac{\partial v_\varphi}{\partial r}+\frac{1}{r^2}\frac{\partial^2 v_\varphi}{\partial \varphi^2}+\frac{\partial^2 v_\varphi}{\partial z^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial \varphi}-\frac{v_\varphi}{r^2}\right)-\frac{1}{\rho r}\frac{\partial p}{\partial \varphi},\quad(2)$$

$$\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\varphi}{r}\frac{\partial v_z}{\partial \varphi}+v_z\frac{\partial v_z}{\partial z}=$$
$$=F_z+\nu\left(\frac{\partial^2 v_z}{\partial r^2}+\frac{1}{r}\frac{\partial v_z}{\partial r}+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial \varphi^2}+\frac{\partial^2 v_z}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p}{\partial z},\quad(3)$$

$$\frac{\partial v_r}{\partial r}+\frac{1}{r}\frac{\partial v_\varphi}{\partial \varphi}+\frac{\partial v_z}{\partial z}+\frac{v_r}{r}=0.\quad(4)$$

The left sides of Equations (1 ÷ 3) represent the inertia forces of the working fluid and the right sides correspond to the forces of mass, viscosity, and pressure in oil [3, 20].

The ring gap presented in Fig. 2 is between a cylindrical piston and a conical cylinder. The piston axis is parallel to the cylinder axis and can be moved by the value of the eccentric e. Practically, the convergence angle α is very small.

The value of the gap height was obtained from:

$$h=\frac{D_1-d}{2}-e\cos\varphi+\frac{(D_2-D_1)z}{2l}\quad(5)$$

where:

D_1, D_2 – the diameter of the cylinder orifice at the inlet and outlet of the gap, respectively,

d – the piston diameter,

φ – the current angular position ($0^\circ \le \varphi \le 360^\circ$),

z – the current axial position ($0 \le z \le l$).

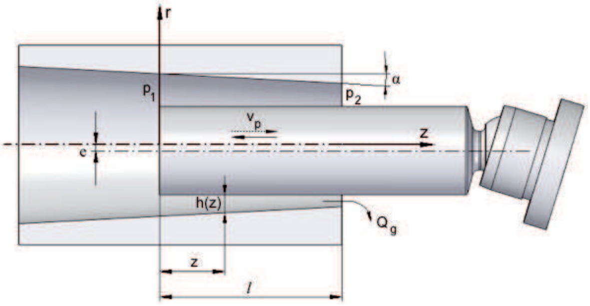

Fig. 2. Confusor gap between the piston and the cylinder in an axial multi-piston pump

The piston moving inwards with the velocity v_p presses the oil out the cylinder chamber. At the same time, due to delivery pressure, the oil flows in the opposite direction to the piston (leakage Q_g). At the gap inlet the pressure is p_1 and at the outlet the pressure is p_2. The gap is of the confusor type if for any longitudinal section the gap height decreases in the direction of oil flow. A characteristic feature of conical gaps is the convergence, described as:

$$m=tg\alpha=\frac{h_2-h_1}{l},\quad(6)$$

where:

h_1, h_2 – are the gap heights at the inlet and outlet, respectively, with the concentric position of the piston in the cylinder.

Additionally, the conical gap can be described by means of the convergence parameter k of the gap:

$$k=\frac{h_2-h_1}{h_1}.\quad(7)$$

The following assumptions were made concerning the fluid flow in the gap:

- the flow is laminar,
- the adjacent surfaces are rigid and do not bend,
- a gap of small height is completely filled with oil,
- tangent stress is Newtonian,
- the fluid is non-compressible with constant viscosity,
- liquid particles directly adjoining to the moving surfaces preserve the liquid velocity,
- inertia forces in the liquid are negligible.

The ratio of the backlash h to the piston radius r in the first and higher orders is also negligible (h/r = 0,0005 ÷ 0,003). Besides, the velocity v_φ of the circumferential flow round the piston is also disregarded. Taking all these assumptions into consideration, the oil flow in the gap is treated as one-dimensional, and the system of equations (1 ÷ 4) is simplified [Nikitin 1982] and becomes:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \mathrm{v}_z}{\partial r}\right)=\frac{1}{\nu\rho}\frac{\partial p}{\partial z}, \tag{8}$$

$$\frac{\partial p}{\partial r}=0, \tag{9}$$

$$\frac{1}{r}\frac{\partial\left(r\mathrm{v}_r\right)}{\partial r}+\frac{\partial \mathrm{v}_z}{\partial z}=0. \tag{10}$$

Let us introduce the dynamic viscosity coefficient μ:

$$\mu=\nu\rho\,, \tag{11}$$

and solve the system of equations (8 ÷ 10), and the formula for the pressure distribution in the conical gap is obtained:

$$p=p_1-\frac{\left(c+k\right)^2\cdot\left[2c\cdot\frac{z}{l}+k\cdot\left(\frac{z}{l}\right)^2\right]}{\left(2c+k\right)\cdot\left(c+k\cdot\frac{z}{l}\right)^2}\cdot$$

$$\cdot\left(p_1-p_2\right)\pm\frac{6\cdot\mu\cdot \mathrm{v}_\mathrm{p}\cdot l}{h_1^2}\cdot\frac{k\cdot\frac{z}{l}\cdot\left(\frac{z}{l}-1\right)}{\left(2c+k\right)\cdot\left(c+k\cdot\frac{z}{l}\right)^2}, \tag{12}$$

where:

$$c=1-\frac{e}{h_1}\cos\varphi\,. \tag{13}$$

RESULTS OF SIMULATIONS OF PRESSURE DISTRIBUTIONS IN CONICAL RING GAPS

Simulations of pressure distribution in conical ring gaps were conducted by means of software.

The following data were assumed for the sake of calculations:

- pressure at the gap inlet p_1 = 32 [MPa],
- pressure at the gap outlet p_2 = 0 [MPa],
- gap length l = 0,042 [m],
- dynamic viscosity coefficient within the range from 0,0122 to 0,0616 [Pas],
- relative velocity of the piston from 0 to 6 [m/s].

Fig. 3 presents oil pressure distribution in a concentric conical gap depending on the gap convergence. In the confusor gap, the pressure grows along the gap (convex curves), and in the diffuser gap the pressure drops along the gap (concave curves). It can also be noted that for the cylindrical gap (m = 0) the pressure drop is linear.

Fig. 4 presents pressure distribution for friction flow of oil through the confusor gap. As can be seen, the influence of piston velocity on the pressure in the gap is significant.

Subsequently, the pressure-friction flow occurring in the majority of ring gaps in hydraulic systems will be discussed.

Fig. 5 presents oil pressure distribution in a concentric conical gap depending on the dynamic viscosity coefficient with the piston moving with the relative velocity of 2 m/s. In the confusor gap (Fig. 5a) the pressure grows together with the dynamic viscosity coefficient, whereas in the diffuser gap (Fig. 5b) the oil pressure decreases as the dynamic viscosity coefficient increases.

Fig. 6 presents pressure distribution in a concentric conical gap depending on the relative velocity of the piston. In the confusor gap (Fig. 6a) the pressure increases with the increase in the relative velocity of the piston, whereas in the diffuser gap (Fig. 6b) the pressure decreases as the relative velocity of the piston increases.

In concentric gaps the pressure around the piston is equal, however in the case of eccentric gaps it varies along the circumference. Fig. 7 presents the distribution of the circumferential pressure for the confusor and diffuser

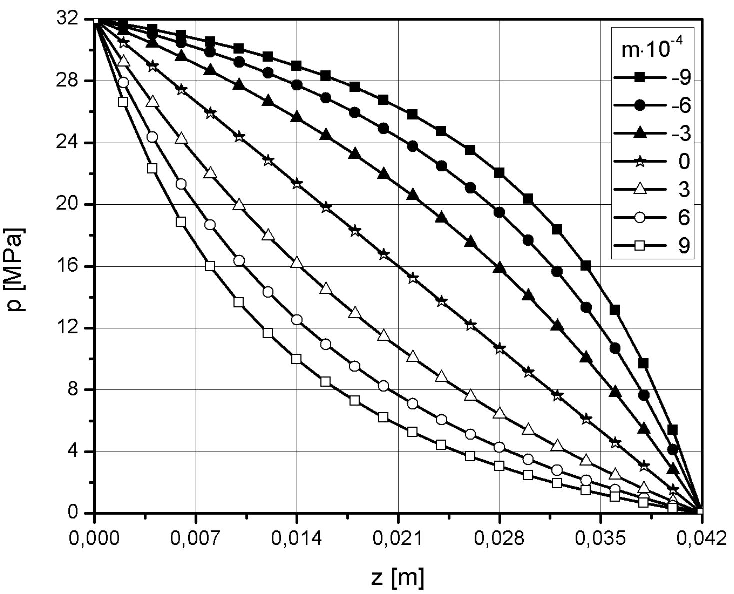

Fig. 3. Pressure distribution in the concentric conical gap with pressure flow depending on the gap convergence direction

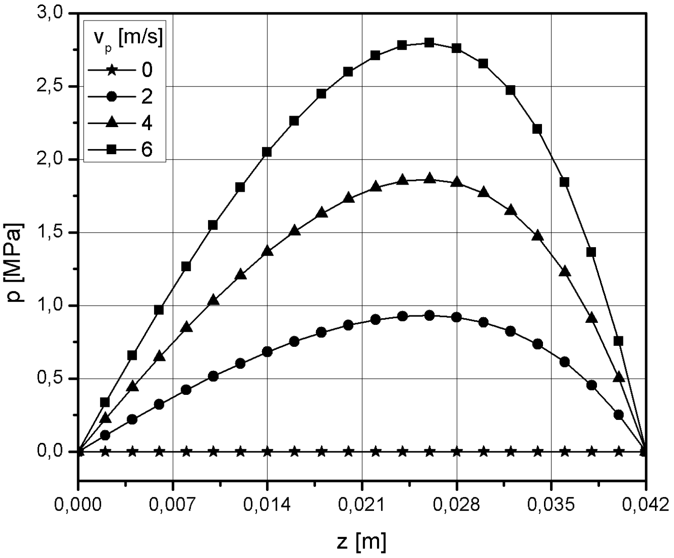

Fig. 4. Pressure distributions in the concentric confusor gap with friction flow, depending on the piston velocity

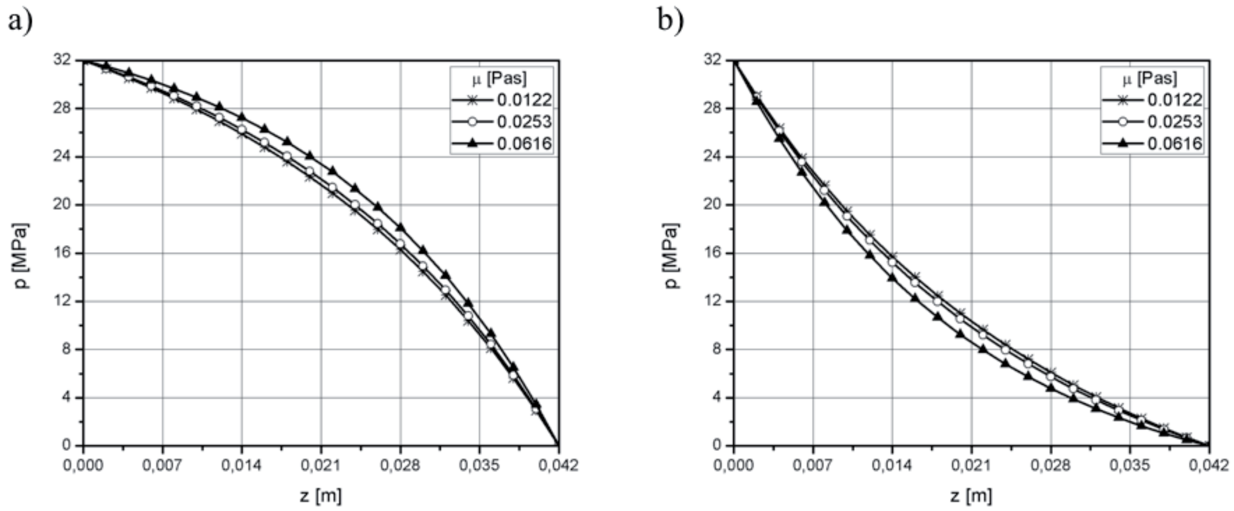

Fig. 5. Pressure distribution in a concentric conical gap depending on the dynamic viscosity coefficient for a) the confusor gap, b) the diffuser gap; with the piston relative velocity v_p = 2 m/s

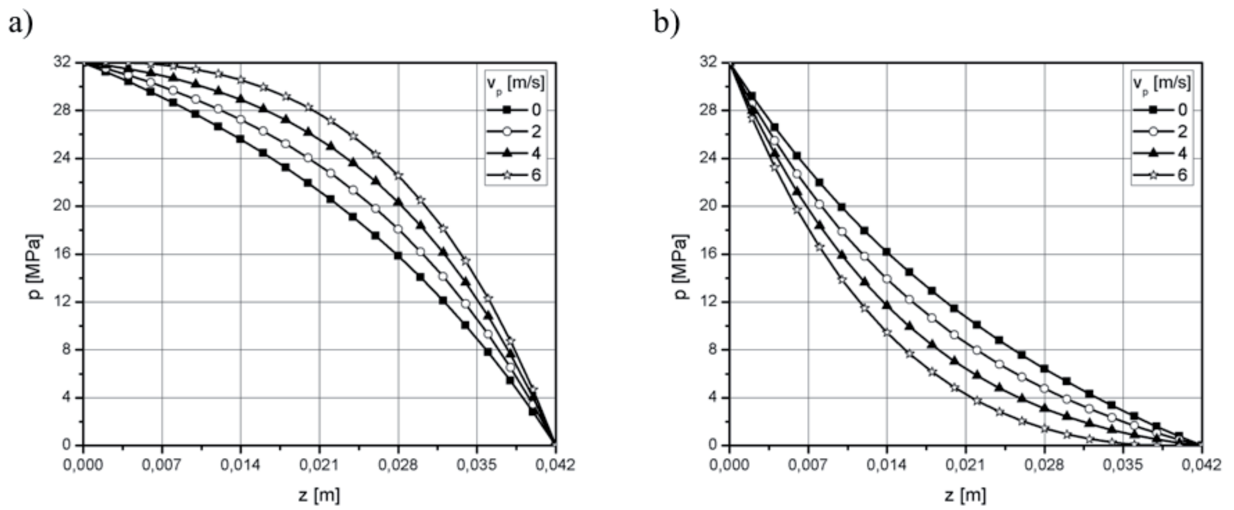

Fig. 6. Pressure distribution in a concentric conical gap depending on the piston velocity for a) the confusor gap, b) the diffuser gap with the oil dynamic viscosity coefficient μ= 0.0616 Pas

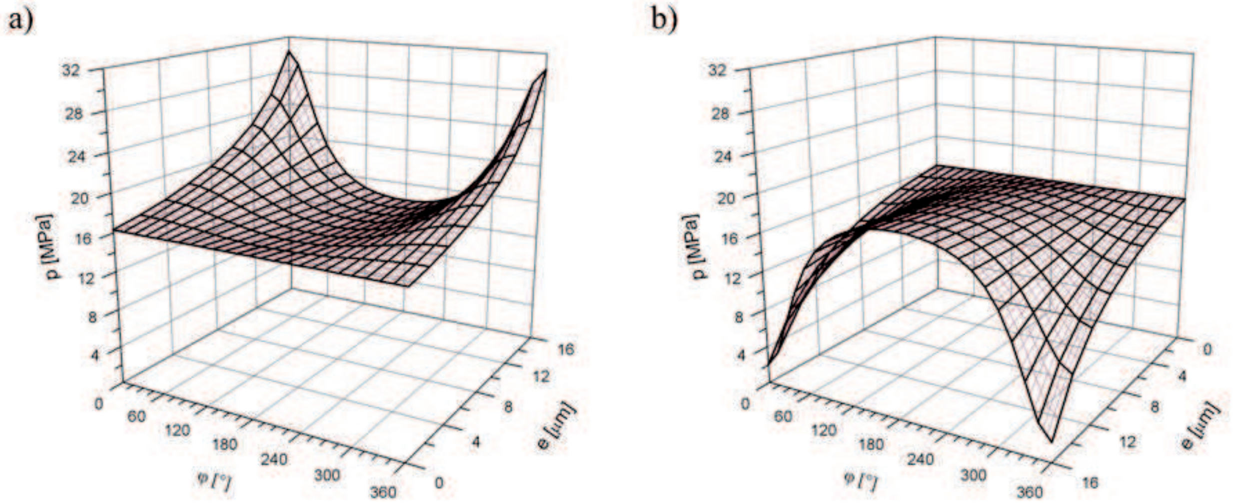

Fig. 7. Circumferential pressure distribution in an eccentric conical gap depending on the piston eccentric value with respect to the cylinder and on the circumferential angle for a) the confusor gap, b) the diffuser gap

gaps depending on the eccentric value *e* of the piston in the cylinder and the circumferential angle φ, with the dynamic viscosity coefficient equal to 0.0253 Pas. In the confusor gap the pressure relieving the piston towards its concentric position increases with the increase in the piston eccentric. In the diffuser gap the pressure under the piston decreases as the piston eccentric increases which leads to the undesirable effect of the piston clinging to cylinder.

CONCLUSIONS

The conducted study leads to the following conclusions:

1. The computational model adopted for the analyses is suitable for determining the pressure distribution in conical ring gaps.
2. In the confusor type ring gaps the pressure increases along the gap, whereas in the diffuser type ring gaps the pressure decreases.
3. Pressure distribution in conical gaps depends to a significant extent on the gap convergence, oil viscosity and its eccentric position.

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ROZKŁADY CIŚNIENIA OLEJU W SZCZELINACH PIERŚCIENIOWYCH STOŻKOWYCH

S t r e s z c z e n i e . W artykule przedstawiono problematykę związaną z przepływami oleju przez szczeliny pierścieniowe występujące w tłokowych pompach i silnikach hydraulicznych. W oparciu o równania Naviera-Stokesa i równanie ciągłości wyznaczono zależność określającą ciśnienie panujące w szczelinie. Rezultaty obliczeń rozkładów ciśnienia w szczelinach konfuzorowych i dyfuzorowych przedstawiono w zależności od lepkości oleju i prędkości względnej tłoczka przy uwzględnieniu mimośrodowego jego położenia.

S ł o w a k l u c z o w e : tłoczek-cylinder pompy, szczelina pierścieniowa, rozkłady ciśnienia.