Comparison of spool radial grooves influence between water and oil hydraulics

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Abstract

In this paper numerical flow calculations with respect to the annular gaps with added radial grooves normaly used on the spools of directional control valves were carried out. The impact of various annular gap geometries and radial grooves during variable pressure conditions, and while using different hydraulic fluids, on the flows through annular gaps were investigated for different flow regimes. Samples with different geometries and numbers of radial groves on the spool of the directional control valve were also made for the purpose of carrying out flow measurements. The two different hydraulic fluids that were used in the numerical simulations and for the flow measurements were a hydraulic mineral oil and tap water. The results of the numerical calculations for the different models of the radial grooves with axially symmetric geometries show their impact on the internal leakage with respect to three different regimes of flow. The results of the numerical calculations based on the use of a hydraulic oil show a trend that was established by the experimental investigation.

KEYWORDS: Hydraulics. radial gaps. labyrinth sealing. directional control valve. spool. leakage. hydraulic mineral oil. tap water. numerical calculations. measurements

1. Introduction

Inside hydraulic components, for example, valves, pumps and motors, there are moving parts that are normally sealed by small annular gaps without any additional elastic seals. These gaps are typically in the size range between one and ten micrometres in the centric position of the spool in the hole. It is generally known that radial grooves reduce the friction between the spool and the hole, but little is known about their influence on the internal leakage through the gap. Nowadays, an ecological approach is very important and the use of water as a hydraulic fluid can protect the environment. However, tap water as a hydraulic pressure medium still poses a lot of unanswered questions /1. 2. 3/. This paper will attempt to answer some of those questions.

Three different types of flow are known:

- Turbulent flow, where the Reynolds number is higher than 2320.
- Laminar flow, where the Reynolds number is between 1 and 2320.
- Stokes flow, where the Reynolds number is lower than 1.

2. Radial grooves and gaps in hydraulic components

The radial gap is the basic element in hydrostatics; it is a channel added to the gap. The literature /4, 5/ describes the triple function of the grooves in hydraulics. The first function of these radial grooves is the normalisation of the pressure in each groove, where the step pressure drop and the centric position of the spool are the consequences. The second function is reducing the radial force on the spool to hole surface. **Figure 1** shows the reduction of the contact force depending on the number of radial grooves. Here, the width of the grooves is always greater than the height. This function is mostly used by the sliding type of directional control valve, where a rapid response without stopping the spool is required.

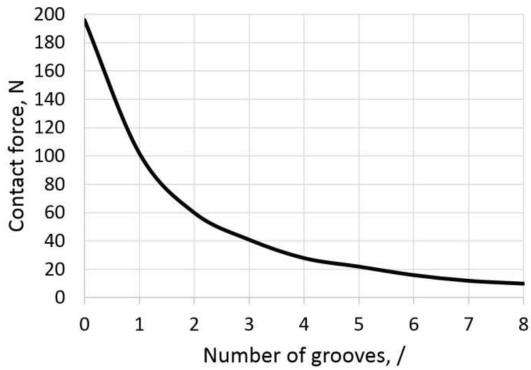


Figure 1: Reduction of the contact force depending on the number of grooves /4/

The third function of the groove /4/ is to reduce the leakage from the gap. It is generally believed that the turbulence flow in a radial groove (**Fig. 2**) can cause a pressure drop from the inlet to the outlet of the groove. In this way the radial grooves simply present a labyrinth sealing /4, 5/. **Figure 3** shows the pressure drop during the flow through four radial grooves /5/.

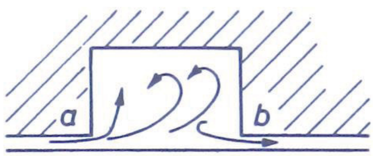


Figure 2: Turbulence of the fluid flow in the radial groove /4/

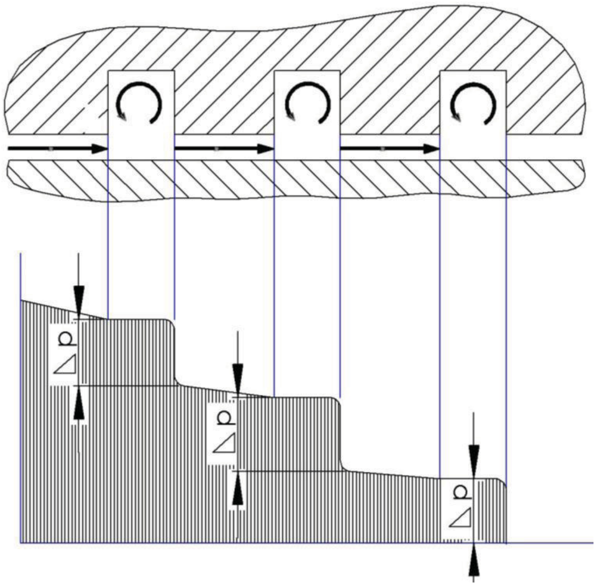


Figure 3: Pressure drop of the fluid flow through three radial grooves /4/

The flow through a smooth radial gap without grooves can be calculated using equation (1), where a Hagen-Poiseuiller laminar flow is considered /6/. This flow through the gap is normally referred to as leakage flow (Q_L).

$$Q_L = \frac{\pi \cdot \Delta p_r \cdot D_{sr} \cdot s^3}{12 \cdot \rho \cdot v \cdot L} \cdot f_{eksc} \tag{1}$$

where Δp_r [Pa] is the pressure difference, D_{sr} [m] is the middle diameter in the gap, s [m] is the height of the gap where the spool is centred in the hole, ρ [kg/m^3] is the density, ν [m^2/s] is the kinematic viscosity of the hydraulic fluid, L [m] is the overlap of the spool in the hole channel and f_{eksc} [/] is a factor of eccentricity for the spool in the hole. For the maximum eccentricity it is 2.5, and 1 for a totally centric position of the spool in the hole.

3. Numerical investigations

First, the numerical investigations will be presented. These are followed by an experimental study of the impact of radial grooves on the leakage in the gap.

3.1. Parameters for the numerical investigations

The presented numerical study investigated the impact of three different groove shapes (**Fig. 4**), three different groove widths, four different numbers of grooves, for five different inlet pressures, three different spool diameters, three different gap heights and two different fluids.

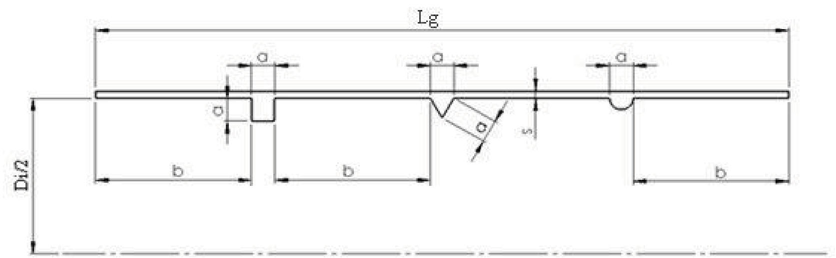


Figure 4: Properties of the numerically and experimentally tested labyrinth groves

Table 1 shows all the parameters employed in the numerical and experimental investigations. All these parameters were first investigated in the numerical study, while the highlighted parameters were additionally verified in the experimental part of this work.

Groove shape / Parameter	Square	Triangular	Semicircular		
Groove width (a) [mm]	**0.3**	0.5	1		
Number of grooves (n) [/]	3	**5**	7	9	
Input pressure (p_1) [bar]	**150**	**200**	**250**	**300**	**350**
Spool diameter (D_i) [mm]	8	**12**	20		
Gap height (s) [mm]	**0.1**	0.01	0.005		
Used hydraulic fluid	**Tap water**	**ISO VG46**			

Table 1: Parameters used in the numerical (all) and experimental (shaded) investigations

Figure 5 shows an example of the dimensional arrangement of five square grooves, where the spool diameter is 12 mm, the groove width is 0.3 mm, its depth is 0.3 mm, the distance between the grooves is 2 mm, the gap height is 0.1 mm and total researched length is 13.5 mm.

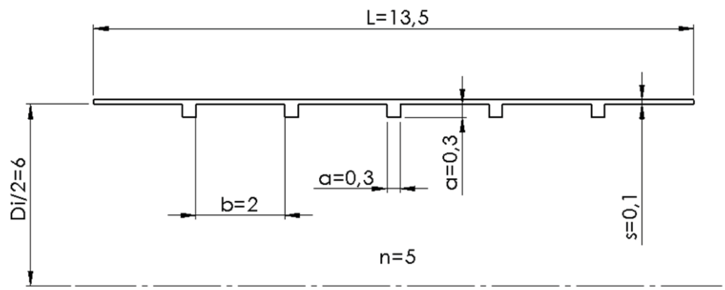
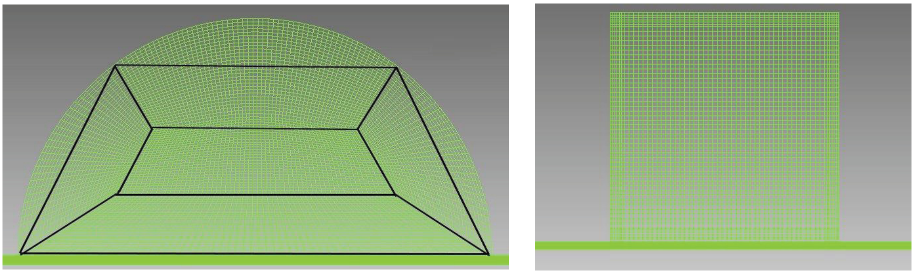


Figure 5: Dimensional arrangement of the five square grooves.

The determination of the mesh on the researched cross-section is the next step in the numerical investigation. Two different types of mesh were used, depending on the geometrical shape of the groove. For the circular type of grooves a structural mesh was used, and for all the angular types (square, triangular) of grooves a non-structural mesh was used, with the aim being to achieve the best results (**Fig. 6**). Numerical investigations were done by software Ansys.



a. b.

Figure 6: a) Circular and b) angular mesh for the numerical analyses

3.2. Results of the numerical investigations

Figure 7 shows the results of the numerical calculations of the flow through the square groove with the gap height of 0.1 mm, with the use of water in the turbulent flow regime. The maximum axial flow velocity (Fig. 7. a) of 134 m/s was observed in the 0.1 mm height of the radial gap; the minimum flow velocity was observed in the middle of the square groove; and the maximum negative flow velocity of -42 m/s was observed at the bottom part of the groove. The maximum positive radial flow velocity was found on the middle inlet side of the groove and the maximum negative radial flow velocity of -61 m/s was found on the opposite side of the groove. The highest turbulence kinetic energy of 696 m^2/s^2 was found near both sharp edges of the square groove.

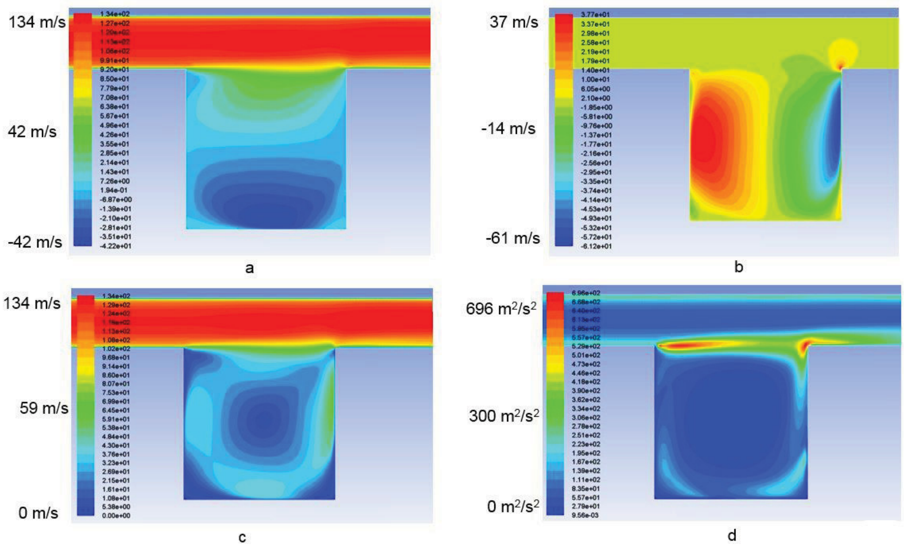


Figure 7: Numerical results for the groove: 0.3 mm (a) and 0.1 mm (s) with water; a) Axial flow velocity. b) Radial flow velocity c) Velocity magnitude. d) Turbulence kinetic energy

Figure 8 shows the results of the numerical calculations of the flow through a square grove with a gap height of 0.1 mm using a hydraulic mineral oil in the laminar flow regime.

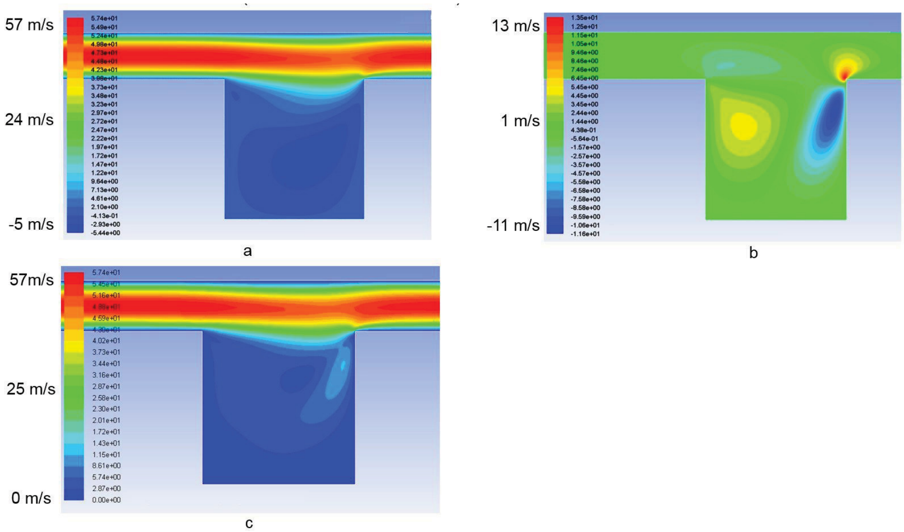


Figure 8: Numerical results for groove: 0.3 mm (a) and 0.1 mm (s) with mineral oil; a) Axial flow velocity. b) Radial flow velocity. c) Velocity magnitude

The maximum axial flow velocity (Fig. 8. a) of 57 m/s was observed in the 0.1 mm height of the radial gap; the minimum flow velocity was observed in the middle of the square groove; and the maximum negative flow velocity of -5 m/s was observed at the bottom part of the groove. The maximum positive radial flow velocity of 13 m/s was found on the outlet edge of the groove and the maximum negative radial flow velocity of -11 m/s was found on the right-hand side of the groove. In the case of the mineral oil a laminar flow was observed, so there are no calculations of the turbulence kinetic energy.

Figure 9 shows the results of the numerical simulations for the water turbulent flow regime for three different shapes of groove with a dimension of 0.3 mm (a) with a gap height of 0.1 mm. It is obvious that the streamlines in the square and semicircular grooves are symmetrical and the streamlines in the triangular groove are in two circles.

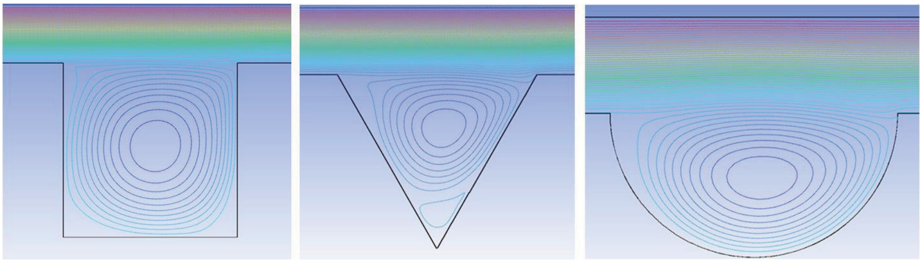


Figure 9: Numerical simulation of the **water** turbulent streamlines for different shapes of groove 0.3 mm (a) and gap 0.1 mm (s)

Figure 10 shows the results of the numerical simulations for the hydraulic mineral oil's laminar flow regime for the same conditions as in the case of the water. It is obvious that the streamlines in all three different shapes are non-symmetrical.

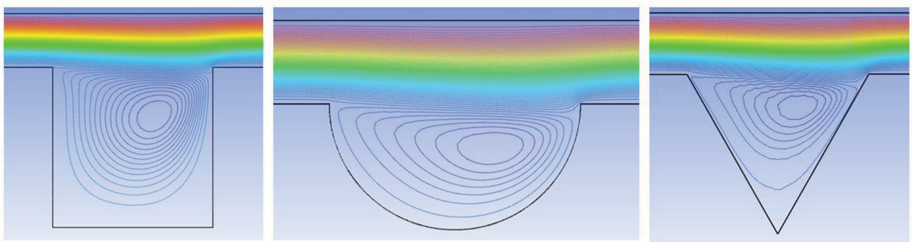


Figure 10: Numerical simulation of the **hydraulic mineral oil** laminar streamlines for different shapes of groove 0.3 mm (a) and gap 0.1 mm (s)

The results of the numerical calculations show that the shape of the grooves has no influence on the pressure drop, the same for the water and for the hydraulic mineral oil.

4. Experimental studies

4.1. Test rig

Two different hydraulic fluids demand two different hydraulic test rigs for water and oil. **Figure 11** shows the water hydraulic circuit of the test rig. The high-pressure water piston type of pump (pos. 2) sucks tap water from the reservoir (pos. 1) and pushes it through the high-pressure water filter (pos. 6) using the hydraulic accumulator (pos. 7) through the open ball valve (pos. 8) to the specimen (pos. 9). The leakage flow through the specimen with different types of spools was measured with a measuring cylinder, timer, pressure and temperature gauge. **Figure 12** shows the employed water hydraulic test rig in the Laboratory for Fluid Power and Controls.

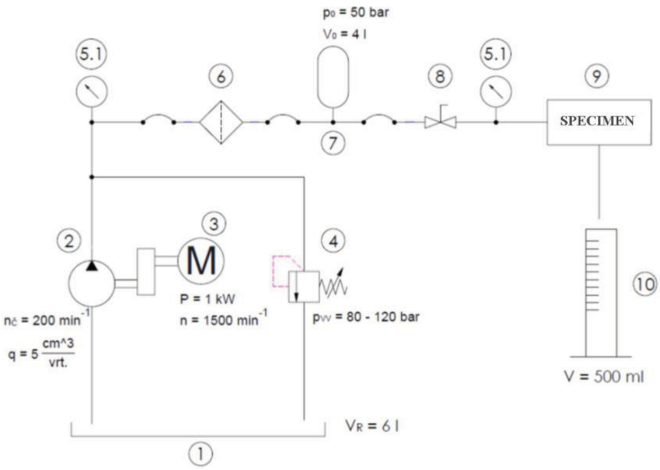
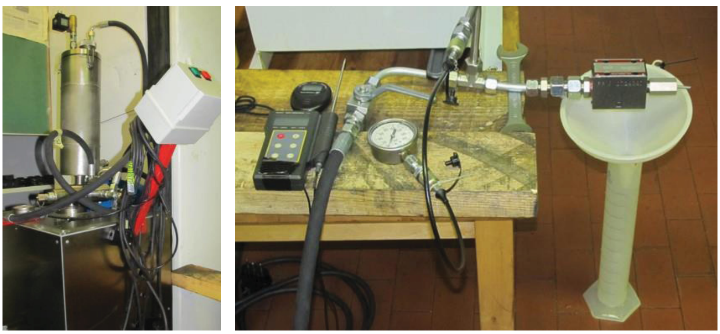


Figure 11: Circuit of the water hydraulic test rig



a b

Figure 12: Water hydraulic test rig. a) power pack. b) tested valve

The oil hydraulic test rig was functionally similar to the presented water hydraulic rig.

4.2. Parameters and procedure

The highlighted parameters in Table 1 show those used in the experimental investigations. **Figure 13** shows ten different customized spools for the standard oil hydraulic directional control valve. The spools were fixed in position in the hole of the directional control valve. The leakage flow was measured at different pressures for a constant temperature. **Table 2** shows the dimensions and their deviations for the tested, customized spools from Figure 13.

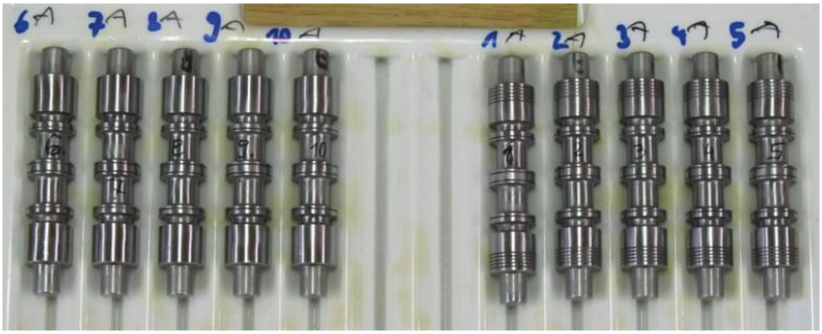


Figure 13: Ten different tested customized spools

Spool Nr.	D_i [mm]	Deviation from cylindricity [µm]	*Rz* [µm]	
1	12.035	1.33	0.63	Spools with radial grooves
2	12.035	0.84	0.524	
3	12.035	1.27	0.608	
4	12.035	1.09	1.536	
5	12.035	1.25	0.802	
6	12.035	1.26	0.671	Spools without radial grooves
7	12.035	0.94	0.733	
8	12.035	2.36	0.627	
9	12.035	2.56	0.63	
10	12.035	1.39	0.668	

Table 2: Measured dimensions of the tested customized spools

4.3. Measurement results

Figure 14 shows the results of the measurements for ten different customized spools with tap-water laminar flow. The highest water leakage flow was observed for spool 7 (0.27 l/min) and with spool 2 (0.25 l/min) and with spool 4 (0.23 l/min) at a pressure of 120 bar. The lowest water leakage was observed with spool 1 (0.07 l/min) and with spool 5 (0.09 l/min) and with spool 3 (0.12 l/min) at 120 bar.

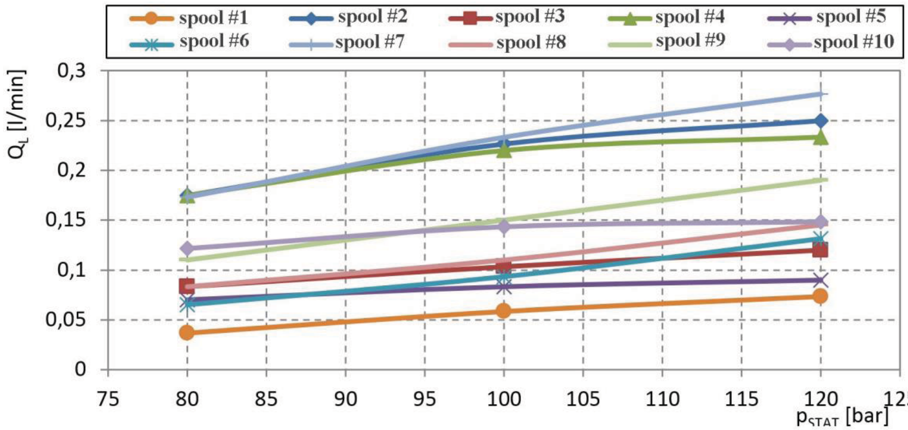


Figure 14: Experimental results for water laminar flow: spool 1–5: Re = 40–270. v = 2.5–16 [m/s]; spool 6–10: Re = 70–300. v = 4–18 [m/s]

Figure 15 shows the results of the measurements for ten different customized spools with hydraulic mineral oil Stokes flow. The maximum mineral oil leakage flow was observed with spool 2 (0.021 l/min) and spool 1 (0.018 l/min) at a pressure of 200 bar. The lowest mineral oil leakage was observed with spool 6 (0.007 l/min) and with spool 9 (0.008 l/min) and spool 7 (0.009 l/min) at 200 bar.

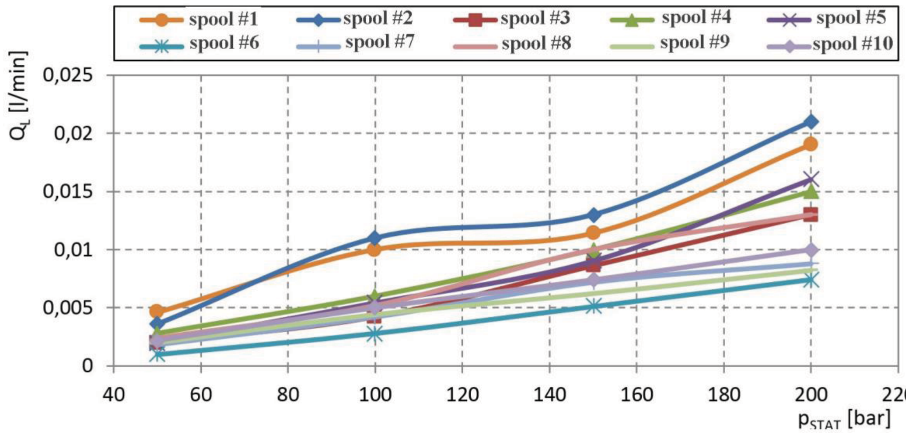


Figure 15: Experimental results for oil – Stokes flow. spool 1–5: Re = 0.01–0.2. v = 0.15–1.4 [m/s]; spool 6–10: Re = 0.01–0.14 . v = 0.07–0.9 [m/s]

The measurement results for the leakage with hydraulic mineral oil show the same trend as the results of the numerical calculations. At low velocities the Stokes flow radial grooves impact on increasing the mineral oil leakage flow.

5. Conclusions

The decrease of the leakage flow in the sliding contact with the radial groves was only observed in the case where a turbulent flow was present. This only happened in the case of the water hydraulic sliding contact with an uncommon height gap.

The flow swirling observed in the numerical simulations for laminar flow does not cause a decrease of the leakage flow through the gap with radial groves.

In hydraulic oil directional sliding type of valves was, due to the higher viscosity of the hydraulic mineral oil, observed as very slow Stokes flow. In this case for the numerical simulations no flow swirling was observed. The consequence was leakage flow through the gaps with the radial groves that was higher than in the case of the smooth gap without radial groves.

The presented work shows that the radial groves in the sliding contact gap increase the leakage, so that their use in order to decrease the leakage is not applicable. The main functions of the radial groves are the pressure relief along the sealing side of the spool and, consequently, centering the spool in the hole to decrease its sliding friction.

6. Acknowledgments

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8. Nomenclature

Δp_r	Pressure difference in the gap	Pa. bar
ρ	Density of the hydraulic fluid	kg/m^3
ν	Kinematic viscosity of the hydraulic fluid	m^2/s. mm^2/s
a	Width and height of the groove	m
b	Distance between the grooves	m
D_i	Spool diameter	m
D_{sr}	Middle diameter of the spool in the gap	m
f_{eksc}	Factor of eccentricity of the spool in the hole	/
L	Overlap of the spool in the hole	m
L_g	Total length of the numerical model	m
n	Number of grooves	/
p_1	Inlet pressure in the gap	Pa. bar
Re	Reynolds flow number	/
q	Displacement of the pump	m^3. cm^3
Q_L	Leakage flow through the radial gap	m^3/s. l/min
S	Height of the gap between the centred spool	m
v	Velocity of the flow streamlines	m/s