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The Gap Seal's Influences on the Leakage and Clamping of Multi-way Directional Valves

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Abstract: Defects coming from processing and assembly inevitably bring geometric and concentricity error to the fitting gap between valve core and frame. To overcome this problem, grooving was proven to be the most simple and effective method to reduce the hydraulic clamping force, and widely used on cylinder valve cores. Theoretically unbalanced forces kept going smaller with the increase of pressure equalizing grooves. When groove width increased, linearly the gap leakage extended. When the width was relatively small leakage was gradually reduced when depth increased. When the width was 1 mm, 1.5 mm or 2 mm, and the depth to width ratio was less than 1, leakage got worse with the increment of depth. *Copyright © 2013 IFSA*

Keywords: Directional valves, Leakage grooves, Dynamic stability.

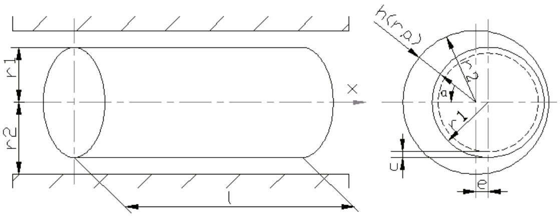
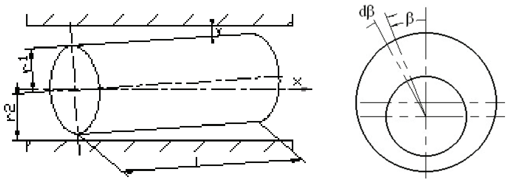
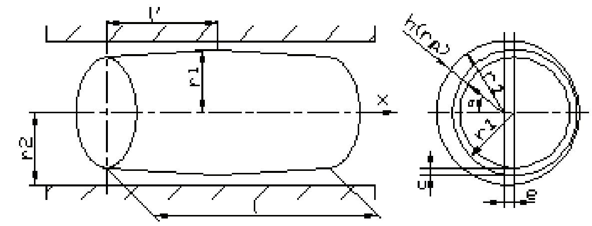
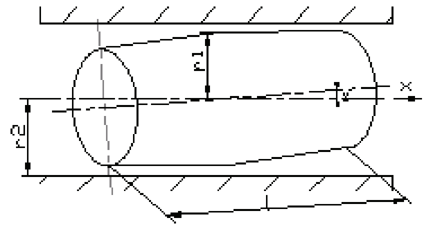
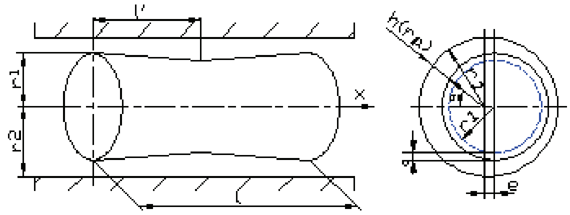
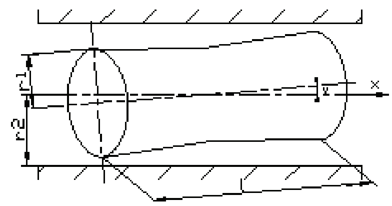
1. Introduction

Gap seal is the kind of seal implemented when there is tiny radial gap with sufficient axial length between components. The sealing performance varied significantly with different types of gap. As given years of experiments, convergence gap sealing was proven to have the minimum leakage, followed by flat type. Expansion ones may be the worst among the three in leakage prevention, but better in dynamic stability [1-4]. Considering the gap between the frame and valve core of a directional valve was a regular cylinder, flat-seal was adopted here.

Massive research on gap seal had been done in last hundred years. However, a more comprehensive proportional valve model is necessary to design and analyze the similarity system. A variety of proportional valve mathematic model, as in [5-7] have described the complexity transformation relationship of the proportional valve electric, proportional valve machine and proportional valve liquid, but did not describe the nonlinear flow characteristics induced by the geometrical feature of valve in the variety flow zone.

Gap size, pressure difference, sealing length and surface quality are major determinants of sealing effects. Thus high geometric accuracy and surface processing demands are posed on the component if chosen for gap sealing. However, defects coming from processing and assembly inevitably bring geometric and concentricity error to the fitting gap between valve core and frame. Several typical gapping structures with tapered angle and eccentricity were listed in Table 1.

Table 1. Various of valve geometry model.

Axis parallel	**No parallel of axis**
 $h = r_2 - r_1 + \frac{c}{l} \cdot x + e \cdot \cos\alpha$ (a)	 $h = r_2 - \frac{r_1}{\cos\gamma} + \frac{c}{l \cdot \cos\gamma} \cdot x + e \cdot \cos\alpha$ (d)
 $h_1 = r_2 - r_1 + \frac{c}{l'} \cdot (x - l') + e \cdot \cos\alpha$ $h_2 = r_2 - r_1 + \frac{c}{(l - l')} \cdot (x - l') + e \cdot \cos\alpha$ (b)	 $h_1 = r_2 - \frac{r_1}{\cos\gamma} + \frac{c}{l' \cdot \cos\gamma} \cdot (x - l') + e \cdot \cos\alpha$ $h_2 = r_2 - \frac{r_1}{\cos\gamma} + \frac{c}{(l - l') \cdot \cos\gamma} \cdot (x - l') + e \cdot \cos\alpha$ (e)
 $h_1 = r_2 - r_1 + \frac{c}{l'} \cdot x + e \cdot \cos\alpha$ $h_2 = r_2 - r_1 + \frac{c}{(l - l')} \cdot (l - x) + e \cdot \cos\alpha$ (c)	 $h_1 = r_2 - \frac{r_1}{\cos\gamma} + \frac{c}{l' \cdot \cos\gamma} \cdot x + e \cdot \cos\alpha$ $h_2 = r_2 - \frac{r_1}{\cos\gamma} + \frac{c}{(l - l') \cdot \cos\gamma} \cdot (l - x) + e \cdot \cos\alpha$ (f)

In which was the eccentricity between inner and outer ring, was the gap at on arbitrary angle. Due to the eccentric phenomenon, was not constant, the specific expression was given in Table 1. In reference [8], Jia studies the radial pressure unbalancing brought by geometry error and coaxial error in a slide valve pair through CFD method. As given in Table 1 (d), clamping was more likely to occur in the case when not only eccentric phenomenon existed between the centerline of the core and the frame, but also the core was an inverted cone. In the following chapters, case (d) in Table 1 was taken as an important scenario for studying the gap flow in the radical gap of a slide valve pair.

2. Compensation Research on Hydraulic Clamping Force and Pressure Equalizing Groove in a Slide Valve

As shown in Fig. 1 that is caused in Table1 (d), in the gap between a valve chamber and a core with length L, the gap length at arbitrary circumferential angle was given as follows.

The expression for pressure at arbitrary h is

$$p = p_1 - ((h_1/h)^2 - 1)/((h_1/h)^2 - 1)\Delta p \, , \quad (1)$$

where

$$h_1 = r_2 - r_1$$
$$h_2 = r_2 - r_1 cor\gamma + c / cor\gamma + e\cos\alpha \quad (2)$$

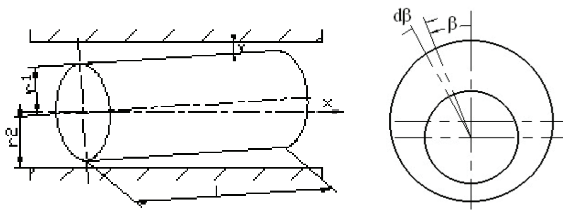


Fig. 1. Gap between a valve chamber and a core with length L.

The force applied on unit width of the circumferential is

$$F' = \int_0^L p\mathrm{d}x =$$
$$\int_0^L \left\{ p_1 - \frac{\Delta p}{(h_1/h_2)^2 - 1}\left[\left(\frac{h_1}{h_1 + (h_2 - h_1)x/L}\right)^2 - 1\right]\right\} dx \quad (3)$$
$$= \left(p_1 - \frac{h_2}{h_1 + h_2}\Delta p\right) L$$

To obtain the force on the core, infinitesimal lengths were taken on circumferential direction, $(d/2)\mathrm{d}\beta$, as shown in Fig. 1. Then the infinitesimal lateral pressure to the eccentric side is given as $F'\mathrm{d}\beta\cos\beta \cdot d/2$.

Note the expression,

$$h_1 = h_{0_1} + e\cos\beta, \;\; h_2 = h_{0_2} + e\cos\beta,$$

where h_{01}, h_{02} is the gap clearance of inlet and out when valve chamber and a valve core were at concentricity, e is the eccentricity clearance, α is the angle measured from where gap clearance was the largest.

Then, the total compression towards the eccentric side on the valve core is expressed in equation,

$$F = \int_0^{2\pi} F' \cdot \frac{d}{2}\cos\beta \mathrm{d}\beta$$
$$= \int_0^{2\pi} \left(\begin{array}{l} p_1 - ((h_{0_2} + e\cos\beta) \\ /(h_{0_1} + h_{0_2} + 2e\cos\beta))\Delta p \end{array} \right) \frac{d}{2} L\cos\beta \mathrm{d}\beta \quad (4)$$
$$= \pi h_{0_2}\left(h_{0_2} - h_{0_1}\right) Ld\Delta p/(4e)\left[1/\sqrt{1 - 4e^2/\left(h_{0_1} + h_{0_2}\right)^2} - 1\right]$$

From Eq. (1), it can be seen that the lateral force, known as the hydraulic clamping force, was related to the clearance height ratio between inlet and outlet, when gap fitting length, eccentricity clearance, and pressure difference were given and fixed.

As shown in the directional valve's profile on Fig. 3, pressure difference existed between the high-pressure oil chamber on the right and the low-pressure oil to the left.

When the valve core is grooved, the lateral radial force decreased when number of pressure grooves increased, as shown in Fig. 2. Since the depths of pressure equalizing grooves were larger than the gap clearance, they gave interconnections to regions with different pressures on the cylinder, and evenly distributed the pressure. Those grooves, on the other hand, divided the cylinder outer rim into sections, flattened unbalanced radial forces, and made the pressure distribution tends to be uniform along the gap axes. Grooving was proven to be the most simple and effective method to reduce the hydraulic clamping force, and widely used on cylinder valve cores.

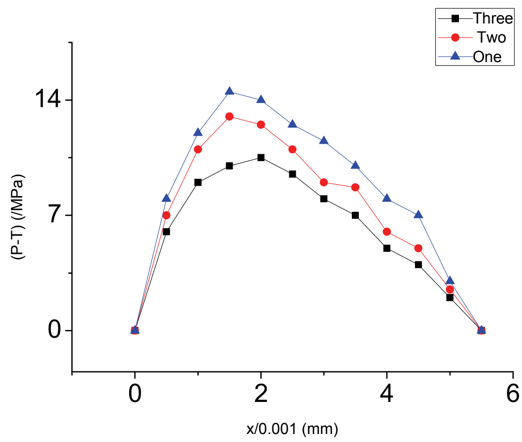


Fig. 2. Result of radial pressure with grooves.

What was important is that the sidewalls of grooves must be done vertically to the outer surface of the core, to avoid oil dirt wedging. The width of grooves must also been maintained constant around the entire circumference, to prevent additional unbalanced forces generated from fluid pressures. On the other hand, theoretically unbalanced forces kept going smaller with the increase of pressure equalizing grooves, the actual problem is that, they brought higher possibility of leakage.

3. Study on the Influence to Gap Sealing, Brought by Pressure Equalizing Grooves

Fig. 3 shows the directional valve's profile. Pressure difference existed between the high-pressure oil chamber on the right and the low-pressure oil to the left. Inter communication was achieved with the directional valve. The valve core was put there to cut off the gap within the walls and oils. Grooves on the core were cut to reduce the hydraulic clamping force, but at the same time increased the risk of leakage.

The following section was presented to address the gapping problem and the optimized design of gap sealing to reduce leakage. Fig. 4 shows a test model of directional valve.

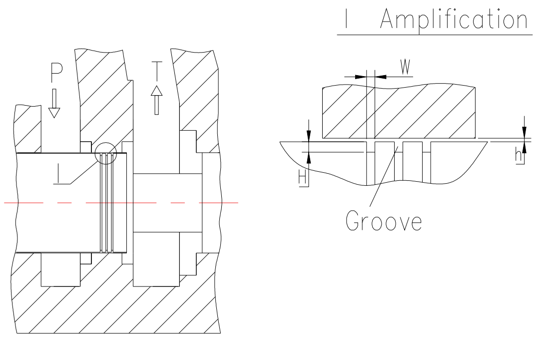


Fig. 3. Directional valve's profile.

Fig. 4. Test model of directional valve.

Previous studies, as in [9] indicated a linear relationship between the flow rate and pressure difference at the inlet. The relationship was in consistency with the Bernoulli equation. Thus only one set of initial pressure boundary condition was needed for the research of gap leakage. All following researches were conducted under such a boundary condition, inlet boundary pressure: 4 MPa, outlet boundary pressure: 0.4 MPa.

3.1. Effect of Groove Width on Leakage

With other initial conditions fixed, studies on the effect of groove width were conducted with several depths of 0.2 mm, 0.5 mm, 1 mm, 1.5 mm and 2 mm. Seen from the Fig. 5, when groove width increased, linearly the gap leakage extended.

3.2. Effect of Groove Depth on Leakage

With the number of grooves fixed, studies on the effect of groove depth were conducted with several widths of 0.2 mm, 0.5 mm, 1 mm, 1.5 mm and 2 mm. The results were given in Fig. 6.

When the width was relatively small, namely 0.2 mm and 0.5 mm, leakage dropped gradually with increment in depth. It was preferred for a gap seal. When the width was 1mm, leakage got worse as the depth went from 0.5 mm to 1.5 mm, but reversibly started to drop again as the depth went beyond 1.5 mm towards 2 mm. With 1.5 mm groove width, leakage continued to increase along with the depth extending from 0.2 mm to 1.5 mm, then turned to alleviation. The overall trend was similar when the width was 2 mm and depth ranging from 0.2 mm to 2 mm.

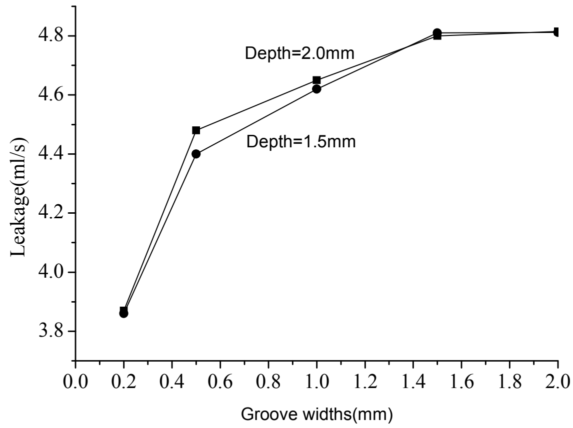


Fig. 5 a. Effect of groove width on leakage.

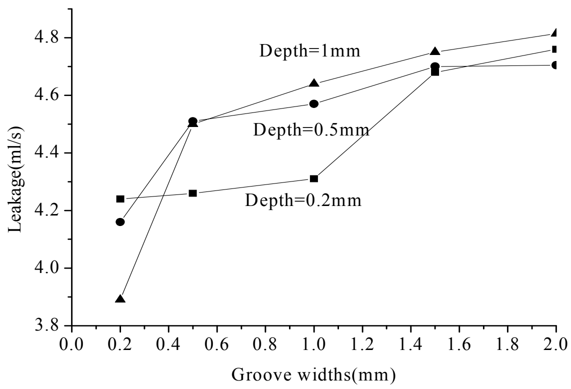


Fig. 5 b. Effect of groove width on leakage.

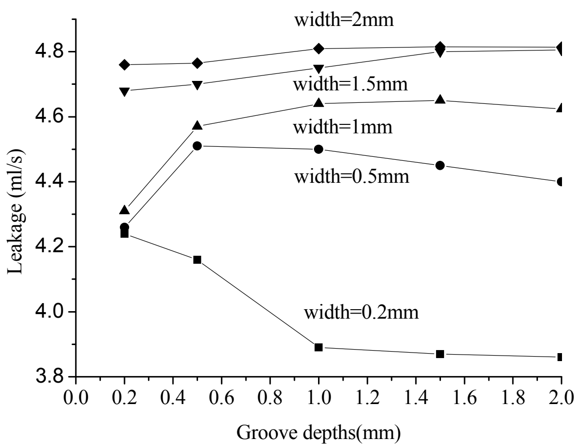


Fig. 6. Effect of groove depth on leakage.

When the width was relatively small, such as 0.2 mm, 0.5 mm, leakage was gradually reduced when depth increased. It was preferred for gap seal. When the width was 1 mm, 1.5 mm or 2 mm, and the depth to width ratio was less than 1mm, leakage got worse with the increment of depth; but it tended to alleviation when that ratio was larger than 1 mm.

4. Conclusions

Defects coming from processing and assembly inevitably bring geometric and concentricity error to the fitting gap between valve core and frame. Clamping was more likely to occur in the case when not only eccentric phenomenon existed between the centerline of the core and the frame, but also when the core is an inverted cone.

When the valve core is grooved, the lateral radial force decreased when number of pressure grooves increased. But grooving also increased the possibility of leakage. That was why the optimization design of groove size was demanded.

When the grooving width was relatively small, gap leakage dropped as the depth increased, and was preferred for sealing. When the width was larger, and was approximately equal to the depth, the leakage expended, grew and turned to alleviation after reaching the maximum.

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