Study on flow field in capacity regulating actuator for reciprocating compressor

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Abstract. The rated capacity of reciprocating compressor tends to be higher than the level needed, so the capacity regulation needs to be implemented to save unnecessary energy waste. Among the methods for reciprocating compressor capacity regulation, holding the suction valves open in partial stroke is a widely used method for its economy, full-range and easy-using characters. The capacity regulation system based on a hydraulic distributor has been successfully applied in industrial process. Hydraulic distributor is the core component of the complete set of stepless capacity regulation system. Continuous high-pressure hydraulic oil provided by hydraulic unit is converted into a pressure impulse wave with a controllable periodic time and pressure acting time when it flows through the hydraulic distributor, which is used to realize the suction valves regulation when it is in the compression stroke. Although the equipment is successfully used in industry fields, the fluid mechanics design of hydraulic distributor is still empirical as its complexity of the fluid field in inner circulation space. For better and more rational distributor design, the flow field in inner zones needs to be better analysed and studied. The manuscript concern ed the subjects of path lines, pressure and velocity distribution in hydraulic distributor’s flow channels using the CFD software FLUENT. The article explored the flow field characteristics and the flow performance with 5.0 MPa outlet pressure. In the end, a systematic conclusion would be given to guide the actor design.

1. Introduction
As the core equipment to provide power in industrial fields, reciprocating compressors are widely used in petroleum and chemical industry. For widely used compressors in the industrial field, the capacity remains constant, while the gas needed tends to be lower than the value. In order to reduce the needless extra input of energy to compress redundant gas, the capacity regulation needs to be implemented to adjust to variable working conditions.

Currently, the main capacity regulation methods for compressor include speed control, clearance pocket, bypass control, the method that holds the suction valves open, etc. \[1,2\]. Speed control is to adjust the motor speed. The method of clearance pocket controls compressor capacity by varying the additional clearance volume manually or automatically \[3\]. Bypass control is a very common method for compressor capacity regulation, but the energy consumed does not reduce. The method that hold the suction valves open is to hold the suction valves open in full compression stroke \[4\] or in partial compression stroke \[5-7\]. Compared with the other, holding the suction valves open in partial compression stroke can achieve full-range and stepless regulation, which has more economic advantages.

Up to now, the main industrial products of holding the suction valves open in partial compression stroke include HydroCOM \[8,9\] and ISC(INfinite stepless controller) \[5\]. Both of them consist of oil
station, control system, electro-hydraulic servo valve, cooling unit, etc. The core units for both are electro-hydraulic servo valves. For the universal conflicts of large flow and high frequency in electro-hydraulic servo valve, some researchers began to explore rotary valves and have made some progress. Juan S. Bacardit [10-12] designed a type of rotary valve, the patents also depicts its structure composition and detailed working process. XI Nanjun [13] designed a new type rotary valve with the shoulder to choke flow, and tested the operating performance in a laboratory prototype. HONG Weirong [14] invented a time based pressing off suction valves device for reciprocating compressor. Compared with the former two, the device in Ref. 15 is entirely made up of mechanical parts, which is more reliable. The device can generate a controllable pressure impulse wave to regulate the suction valves. For the complexity of inner fluid field, traditional experiential design is the major design methodology. For a mature product, the flow fields in inner zones need to be better analyzed and studied.

2. Structure and operation theory
Hydraulic distributor consists of hydraulic and control system. The function of a hydraulic distributor was to convert continuous high-pressure hydraulic oil into a periodic pressure impulse wave, which was used to realize the suction valves regulation when in compression stroke. Figure.1 shows the assembly sketch of the hydraulic distributor. The main components include the outer sleeve, the middle sleeve and the central rotation axis. The outer sleeve is glidingly connected with the middle sleeve using a feather key. There are two sets of pressure zone and release zone along the circumference of the central axis. The middle sleeve can be moved to the left or right along the axial direction, so the relative position of oil outlet and pressure zone is changed. High pressure oil flows through oil inlet, annular groove, oil hole, axial flow channel, radial flow channel, and finally reaches to pressure zone of central rotation axis. When axial groove in middle sleeve connects to pressure zone, oil passes through axial groove and oil outlet, and then acts on unloader to press off suction valves. When axial groove connects to release zone, oil in unloader goes back through oil outlet and axial groove to release zone, passes through inner flow channel to oil return port, eventually flows into oil station.

![Figure 1. Assembly sketch of hydraulic distributor.](image-url)

3. Computational flood dynamics
Structure complexity may cause more energy loss and the rapid changes of the flow field structure will generate cavitation or vortex. The article focused on the flow characteristic of oil supply process, and neglected the rotation of central rotation axis. Calculation condition was set to 100% capacity
operation condition. Considering that force of executing fork should be greater than gas reverse thrust, the oil outlet pressure of oil outlet is set to 5.0 MPa.

3.1. Physical model
To study the oil flow in hydraulic distributor internal flow channels, physical model of flow channels should be firstly built. The main dimension is listed in Table 1. The 3-D model of internal flow channels was built using the pre-processing software GAMBIT.

| No | Geometry of flow channel | Dimension, mm |
|----|--------------------------|---------------|
| 1  | Oil Inlet                | Diameter 16, Length 20 |
| 2  | Annular Groove           | Out radius 60, Inner radius 55 |
| 3  | Oil Hole                 | Diameter 5, Length 15 |
| 4  | Radial flow Channel      | Diameter 5 |
| 5  | Axial flow Channel       | Diameter 8 |
| 6  | Oil Outlet               | Diameter 16, Length 20 |

3.2. Finite element model and numerical method
For pipe flow, Reynolds number is the important parameter of flow characteristics. In the normal operating condition, the oil pump flow rate Q was 25 L/min, the Reynolds numbers in the maximum and minimum diameter were calculated respectively. The results are shown in Table 2.

| Diameter(m) | Flow rate(L/min) | Velocity(m/s) | Density(kg/m³) | Dynamic viscosity(Pa·s) | Re   |
|-------------|------------------|--------------|----------------|-------------------------|------|
| 0.016 (Max.) | 25               | 2.07         | 876            | 4.03e-2                 | 721  |
| 0.005 (Min.) | 25               | 21.2         | 876            | 4.03e-2                 | 2307 |

So the oil flow in internal flow channels remains laminar state. The model is calculated by CFD software FLUENT. The boundary condition of oil inlet adopts velocity-inlet condition, and oil outlet adopts pressure-outlet condition. Unstructured tetrahedral mesh is employed and grid cell number is 1.75 million. The calculation domain is shown in Figure 2.

![Figure 2. Calculation domain.](image)

4. Result and analysis
4.1. Velocity distribution
The velocity contour of flow channel section is shown in Figure 3. As can be seen from the contour, velocity of the annular groove is very small, and the velocity is circumferential flow to fill the annular
groove. Pipe I in the figure, velocity direction changes in 90-degree when oil flows into axial channel from radial channels. Considering that oil of four radial channels flows into axial channel at the same time, velocity of axial channel increases to a certain degree. Compared with pipe I, oil in pipe II and III is similar to pipe I that velocity direction changes in 90-degree. In pipe II, oil flows into radial channel from axial channel. Flow direction changes because of the restraint of radial flow channel wall forming a 90 arc transition. Under the action of centrifugal force, fluid away from the axial channel outlet contracts to achieve a higher velocity. The same situation applies to pipe III.

Figure 3. Velocity distribution on flow channel section.

Figure 4 shows the velocity vector of position A in Figure.3. Flow direction changes and velocity distribution is readjusted. In position b, fluid diffusion produces concave wall eddy current with the flowing area increasing. In position c, fluid gathers near the outer wall due to the centrifugal force. Fluid contracts and the velocity increases. For position a, fluid diffusion forms the convex wall eddy current phenomenon. Because of the difference of centrifugal force acting on fluid, secondary flow phenomena will emerge in pipe cross-section.

Figure 4. Velocity vector of position A.

To study oil speed distribution after flowing through the internal channels, pipe I, II, III and IV positions are chosen to observe the sectional velocity distribution. The results are shown in Figure.5. As is shown in velocity vector of pipe I export cross section, the velocity is uniformly distributed. Because it is the starting position where the velocity direction changes in 90-degree, velocity has a
certain angle to the channel axis direction. For pipe Ⅱ, radial channel export connects to pressure zone, and the velocity keeps in the same direction with the axis. There still exists a certain degree velocity gradient at the channel exit section. In pipe Ⅲ, velocity keeps along channel axis direction. Due to the fluid viscosity, velocity near the wall is a little smaller. In pipe Ⅳ, velocity decreases significantly due to the increase of channel diameter. Analysis shows that the secondary flow plays an important role on velocity redistribution.

Figure 5. Velocity vector of export cross section.

4.2. Pressure distribution
Figure 6 shows the static pressure and total pressure distribution along the flow channel section. What can be seen from the figure is that pressure decreases gradually along the flow direction. Static pressure and total pressure are the maximum value at position of oil inlet, and the value is about 5.38 MPa. Static pressure and total pressure of oil outlet are the minimum value 5.0 MPa. Due to the molecular viscosity and eddy current effect, the pressure loss is about 0.38 MPa. Compared with static pressure and total pressure.
pressure distribution, total pressure is obviously higher than static pressure in pipe I, II, III and IV for the dynamic pressure effect.

4.3. Path lines analysis
Figure 7 shows the path lines in flow channels under setting condition. Small-size vortex forms when oil flows into the annular groove from oil hole. There is a small scale oil dead zone in triangle vertices region in pressure zone which is far away from oil export. Besides, the velocity is perpendicular to the middle sleeve wall when oil flows into the annular groove. The calculating data indicates that there is about 4.96 N vertical force acting on the middle sleeve wall. This will make the middle sleeve produce a certain angle inclination, which is the reason for middle sleeve’s stuck phenomenon.

![Path lines in flow channels](image.png)

**Figure 7. Path lines in flow channels.**

5. Conclusion
In this research, the flow inside the hydraulic distributor was analyzed by numerical simulation. The pressure distribution, velocity distribution and path lines of 100% operation condition were studied, and the following conclusions could be reached:

1) As is shown in the velocity contour, in the position where internal channels direction changes in 90-degree, the impact of the fluid to the surface is large. Referring to available literatures, a 90 arc transition can be adopted to reduce the impact, and circular arc transition can also alleviate the eddy current to some extent. For radial channel export, there is still a large velocity gradient near the export. The method to increase flow channel length can be considered to reduce the velocity gradient.

2) Oil pressure decreases gradually along the flow direction, the pressure of oil inlet is the highest and the oil outlet is the minimum.

3) As can be seen from path lines, the flow of oil in hydraulic distributor is very regular. There is only small scale vortex flow in the area where oil flows into the annular groove from oil hole, and there is small scale dead zone in the region of the triangle vertices in pressure zone which is far away from oil export. For the impact acting on the middle sleeve wall, we can change the position of oil inlet to right below hydraulic distributor. The impact force can balance the gravity of middle sleeve and central rotation axis.

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