Pressure transformation ratio characteristics of kidney-shaped holes variable four-port hydraulic transformer

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Abstract: The kidney-shaped holes variable four-port hydraulic transformer of inlet and outlet equal flow is proposed, such as the theory, the flow of port A and port B is the same and equivalent to a hydraulic motor. The flow of ports O and T is the same, and the equivalent of a hydraulic pump. The A and B kidney-shaped holes of the valve plate are the same. The O and T kidney-shaped holes are the same. The transformer ratio can be changed by adjusting the control angle of the valve plate. The mathematic models of displacement, angular torque, and pressure transformation ratio about the four-port hydraulic transformer are built. The derivative relationship between the pressure transformation ratio and flow of port B, recycling pressure difference, and viscosity is deduced, respectively. Based on it, the influence characteristics of the three factors on the pressure transformation ratio are obtained. The result of theoretical analysis and simulation shows that the increment in the flow of load circuits leads to a decrease in the pressure transformation ratio, while the decrease in viscosity and the increment in recycling pressure difference lead to an increase in the pressure transformation ratio.

1 Introduction

The existing hydraulic equipment generally adopts less pump and multi-load hydraulic system, and the maximum load can be driven only when the hydraulic pump output pressure is higher than the maximum load pressure. If the load pressure varies greatly, the oil supplied by the system to the low-pressure load loop is throttled by the proportional control valve, which causes great pressure loss, leading to the low efficiency of the system and increasing oil temperature. More powerful cooling equipment must be installed to bring the oil temperature down to the required range of the hydraulic system, thus further increasing the power consumption. In addition, nowadays, hydraulic equipment, especially construction machinery, most of them adopt a valve-controlled load hydraulic system, integrating a multi-channel reversing valve and a variable-volume pump to match with specific load, it is difficult to change the existing hydraulic system structure and process, but it has the problems of throttling and inefficiency [1].

Common pressure rail (CPR) is a new hydraulic system platform for environmental protection, energy conservation, and emission reduction. It can be used in construction machinery, automobiles, and test equipment [2–4]. The structure of the CPR system is similar to the power grid. Multiple components in the system can be independently controlled to increase system efficiency, further simplifying system architecture and reducing costs. The CPR system requires a hydraulic transformer to adjust the pressure of the system to match the load pressure so that each actuator with different load pressure can obtain the required pressure, thus reducing the throttling loss and heating of the hydraulic system [5–7].

The traditional hydraulic transformer composed of a coaxial rigid connection of a hydraulic pump and hydraulic motor, which has a complicated structure, large volume and weight, low recovery efficiency, and high cost, so it cannot be widely popularised and applied [8]. There are three slots (A, B, T) of the same size on the valve plate of the new type hydraulic transformer. The transformer ratio of the new type hydraulic transformer is defined as the ratio of the pressure of port B to port A. The flow ratio at ports A and B is the reciprocal of the pressure ratio. If ports A and B of the new type of hydraulic transformer are connected to the hydraulic load circuit in series, when the pressure of the load circuit changes with the working condition, after passing through the hydraulic transformer, the flow output from port B changes with the working condition [9–11]. This makes it difficult to control the flow in the load. When multiple loads operate at the same time, the manoeuvrability of the devices is very poor. Therefore, the new hydraulic transformer is mainly used for the secondary pressure regulation of the CPR and cannot be directly connected to the existing valve-controlled load hydraulic circuit to reduce the throttling loss of the hydraulic system. To avoid throttling loss and recover differential pressure energy, braking energy and gravitational potential energy without changing the original hydraulic system, and realise system unthrottled pressure matching, thereby improving system efficiency and reducing system installed power. Therefore, the four-port hydraulic transformer with variable kidney-shaped holes is put forward in this paper, and its pressure transformation ratio characteristics are analysed theoretically. It is of great significance to provide a theoretical basis for the design of hydraulic transformers.

2 Four-port hydraulic transformer with variable kidney-shaped holes

2.1 Structure and principle

Four-port hydraulic transformer with variable kidney-shaped holes is shown in Fig. 1. It is mainly composed of a valve plate shaft, end cover, balanced valve plate, balanced cover, distributor cover, valve plate, cylinder block, plunger, and driving plate [12]. There are seven plunger holes uniformly arranged on the cylinder body. The centre line of the plunger hole is parallel to the central axis of the cylinder body, and each plunger hole is provided with a plunger. The right end of the plunger is hinged with the driving plate through the spherical end of the connecting rod. The valve plate and the balanced valve plate have the same structure. They are concentrically fixed on the valve plate shaft and can be rotated together. Both of them are equipped with two symmetrical waist grooves. The two sides of the valve plate are attached to the distributor cover and cylinder through the oil film, respectively, and the two sides of the balanced valve plate adhere to the end cover and balanced cover through the oil film, respectively. The balanced cover and distributor cover are rigidly connected. The balanced cover has four oil ports and the distributor cover has the same structure as it.

There are two isolators $K_{OA}$ and $K_{BT}$ on the balanced cover and the distributor cover. The two isolators on the distributor cover are...
located at the same position as the top dead centre (TDC) and bottom dead centre (BDC) of the cylinder block, respectively. The width and height of the isolators are the same as the width and height of the waist groove of the distributor cover. After the balanced cover and distributor cover are matched with the balanced valve plate and valve plate, the isolation block isolates the two waist grooves of the balanced valve plate and valve plate into four waist grooves. The four waist grooves are connected to four oil ports of the balanced cover and flow distributor cover, respectively. During the working process of the hydraulic transformer, the corresponding oil ports on the distributor cover and balanced cover are connected through the external oil circuit, i.e. port A1 is connected to A2, B1 to B2, O1 to O2, T1 to T2, which makes the valve of the torque produced by the oil to the balanced valve plate is the same as the torque produced by the valve plate, while in the opposite direction. As the position of the isolation block remains unchanged, the length of the four waist grooves of the valve plate can be changed by rotating the valve plate shaft, i.e. the displacement of the plunger connected to each port is changed. Thus, the ratio of the pressure difference between the recovery oil port O and the low pressure oil suction port T and the pressure difference between the high pressure oil port A and the low pressure oil port B is changed, and the function of changing pressure is realised. Moreover, the four waist grooves are separated by two isolators \( K_{OA} \) and \( K_{BT} \), and the four waist grooves do not cross the TDC and BDC, which avoids the phenomenon of oil absorption and drainage in the plunger connected with the same waist groove. The valve plate, balanced valve plate, cylinder block, and driving plate can rotate along their central axes, respectively, and there is a certain angle between the central axes of the valve plate and cylinder block and the central axes of the drive plate.

The overlapping structure diagram of the valve plate and distributor cover is shown in Fig. 2. One side of the valve plate matches the cylinder block, while the other side matches the distributor cover. According to Fig. 2, the position of the waist groove of the valve plate, the plunger hole of the cylinder body and the radial hole of the valve cover can be seen. The waist grooves A, B, O and T of the valve plate are connected to the radial holes A1, B1, O1, and T1 of the distributor cover, respectively.

If port A is the high-pressure oil inlet, B is the low-pressure oil outlet, O is the oil recovery outlet, and T is the low-pressure oil filling outlet, the working process of the four-port hydraulic transformer under this working condition is as follows.

When port A1 of the distribution cover is connected to high-pressure oil, the oil flows into port A1 of the distributor cover and flows into plunger hole connected to it through port A of the valve plate, it exerts a force on the plunger to extend out of the plunger hole, at the same time, the force acts on the driving plate through the plunger rod and generates a torque, which makes the driving plate rotate. Depending on the position of the waist groove of the valve plate, the plunger hole of the cylinder body and the radial hole of the valve cover can be seen. The waist grooves A, B, O and T of the valve plate are connected to the radial holes A1, B1, O1, and T1 of the distributor cover, respectively.

When port A1 of the distribution cover is connected to high-pressure oil, the oil flows into port A1 of the distributor cover and flows into plunger hole connected to it through port A of the valve plate, it exerts a force on the plunger to extend out of the plunger hole, at the same time, the force acts on the driving plate through the plunger rod and generates a torque, which makes the driving plate rotate. Depending on the position of the waist groove of the valve plate, the plunger hole of the cylinder body and the radial hole of the valve cover can be seen. The waist grooves A, B, O and T of the valve plate are connected to the radial holes A1, B1, O1, and T1 of the distributor cover, respectively.

(1) When the plunger hole turns to connect to port T, the plunger hole will absorb oil through port T, and port T completes the oil-absorbing function of the hydraulic pump.

(2) After the column plug hole rotates past the BDC, the plunger starts to retract into the plunger hole under the action of the driving plate, oil is discharged through port B, and port B completes the oil draining function of the hydraulic motor.

(3) When the plunger hole is turned to connect to the O waist groove, the driving plate acting on the plunger causes the hydraulic oil to be discharged from port O, and port O completes the oil discharging function of the hydraulic pump. With the rotation of the cylinder block, the column plug hole is connected to A again.

The cylinder body of a combination, the cylinder rotates one cycle, and all the plungers suck or drain oil from the four kidney-shaped holes. The four-port hydraulic transformer with kidney-shaped holes is equivalent to the combination of a hydraulic motor and a hydraulic pump. In this condition, the differential pressure energy between port A and port B can be recovered, and the recovered high-pressure oil can be discharged from port O and reused. If ports A1 and B1 are exchanged, and ports O1 and T1 are exchanged, the cylinder body will rotate clockwise. The differential pressure energy between ports B1 and A1 can still be recovered. If O1 is connected to the high-pressure inlet pipe, A1 to the low-pressure outlet pipe (connected to the load), and T1 and B1 to the oil tank, the hydraulic transformer releases the recovered hydraulic energy. If A1 is connected to the high-pressure inlet pipe, O1 to the...
2.2 Symbols of the four-port hydraulic transformer

The comprehensive function symbol of the four-port hydraulic transformer with variable kidney-shaped holes is defined as shown in Fig. 3.

In Fig. 3a, the ellipse represents the shell of the hydraulic transformer. $P_A$, $P_B$, $P_O$, and $P_T$ represent the high-pressure oil inlet, low-pressure oil outlet, oil recovery outlet, and low-pressure oil suction outlet, respectively. The arrow represents the adjustable angle of the valve plate, and the black triangle inside represents the direction of the oil. There are two triangles for each oil port, which indicates that each oil port is either in or out of oil under different working conditions. The line between the diagonal orifices indicates that the flow rates of the two diagonal orifices are equal. The black semicircle between $P_A$ and $P_O$ represents isolation block $K_{AO}$, and the black semicircle between $P_B$ and $P_T$ represents isolation block $K_{BT}$. Fig. 3b shows the four functional symbols of the inlet and outlet oil connection under different recovery conditions of the hydraulic transformer, and Fig. 3c shows the four functional symbols of the inlet and outlet oil connection under different release conditions of the hydraulic transformer.

2.3 Function of the four-port hydraulic

The hydraulic transformer with variable kidney-shaped holes proposed in this paper has four oil ports. The flow rate of $P_A$ inlet and $P_B$ outlet is the same. Ports $P_A$ and $P_B$ can be strung into the load pipeline where pressure reduction is required, and the differential pressure energy lost by the original system can be recovered without changing the load flow rate. If ports $P_O$ and $P_T$ are connected to the tank, the four-port hydraulic transformer has the same function as the new three-port hydraulic transformer, it also has all features of the new hydraulic transformer. For example, the system efficiency can be improved, liquid energy can be recycled or directly used, oil pressure can be increased or reduced, and four-quadrant operations can be achieved [13].

3 Mathematical models of four-port hydraulic transformer

The control angle of the valve plate is defined as the angle between the symmetrical centre line of the transition zone of waist grooves $A$ and $T$ and the connection line of TDC and BDC. The length of the four ports $A$, $B$, $O$, and $T$ of the valve plate changes with the control angle of the valve plate. $A$ port is the high-pressure oil inlet, $B$ port is the low-pressure oil outlet, $O$ port is the recovery oil outlet, and $T$ port is the low-pressure oil filling port. The corresponding relationship between the kidney-shaped holes angle of the valve plate and the control angle of the valve plate is shown in Fig. 4. Two isolation blocks, $K_{AO}$ and $K_{BT}$, which are fixed with the distributor cover and are not rotated with the valve plate, separate the kidney-shaped holes of $A$ and $O$, $B$ and $T$, respectively.

3.1 Mathematical models of the displacement

As can be seen from Fig. 4, there are the following relationships among the parameters:

$$\alpha_A = \theta$$  \hspace{1cm} (1)

$$\alpha_O = \pi - \theta$$  \hspace{1cm} (2)

$$\alpha_B = \theta$$  \hspace{1cm} (3)

$$\alpha_T = \pi - \theta$$  \hspace{1cm} (4)

where $\alpha_A$, $\alpha_B$, $\alpha_O$, and $\alpha_T$ is the effective wrapping angles of port $A$, $B$, $O$, and $T$ ($\circ$), respectively. $\theta$ is the control angle of the valve plate, the value of $\theta$ ranges from $0^\circ$ to $180^\circ$, and $\alpha_A + \alpha_O + \alpha_B + \alpha_T = 360^\circ$.

Based on the kinematics analysis of the plunger [14, 15], the displacement of the four slots $A$, $B$, $O$, and $T$ can be calculated.
\[ V_A = \frac{K}{2\pi} \sin \frac{\theta}{2} \]  
(5)  

\[ V_B = -\frac{K}{2\pi} \sin \frac{\theta}{2} \]  
(6)  

\[ V_T = \frac{K}{2\pi} \cos \frac{\theta}{2} \]  
(7)  

\[ T = \frac{K}{2\pi} \cos \frac{\theta}{2} \]  
(8)

where \(V_A\), \(V_B\), \(V_T\), and \(V_T\) are the displacements of ports \(A\), \(B\), \(O\), and \(T\), respectively, \(K = \pi z r \sin \beta\), where \(K\) is the cross-sectional area of the column plug hole, \(z\) is the number of plungers, \(\beta\) is the angle between the drive shaft and the centre line of the cylinder, \(r\) is the distribution circle radius of the connecting rod ball head on the spindle disc. It can be seen from (5)–(8) that the two oil ports \(A\) and \(B\), respectively. \(O\) is the same as port \(B\), and the flow of port \(T\) is the same as port \(O\).

### 3.2 Mathematical models of torque

From the working principle of the four-port hydraulic transformer, it can be seen that the two oil ports \(A\) and \(B\) are equivalent to a hydraulic motor, and the two oil ports \(O\) and \(T\) are equivalent to a hydraulic pump. The theoretical output torque of port \(A\) to port \(B\) is as follows [16]:

\[ T_{AB} = \Delta P_{AB} V_A \]  
(9)

where \(\Delta P_{AB} = p_A - p_B\).

The actual output torque of port \(A\) to port \(B\) is shown as follows:

\[ T_{ABr} = T_{AB} - \Delta T_{PAB} - \Delta T_{VAB} \]  
(10)

\[ \Delta T_{PAB} = \frac{C_m}{V_{AB}} \]  
(11)

\[ \Delta T_{VAB} = \frac{C_m}{V_{AB}} \]  
(12)

where \(\Delta T_{PAB}\) is the friction torque loss caused by pressure, which is equivalent to the constant loss caused by hysteresis and eddy current in power transformer. \(\Delta T_{VAB}\) is the frictional torque loss caused by medium viscosity, which is equivalent to the variable loss in a power transformer proportional to the square of the current. \(C_m\) is the mechanical friction torque loss coefficient. \(\mu\) is the coefficient of friction of working oil. \(\omega\) is the rotational angular velocity of the cylinder block.

The theoretical output torque of port \(O\) to port \(T\) is as follows:

\[ T_{OT} = \Delta P_{OT} V_O \]  
(11)

where \(\Delta P_{OT} = p_O - p_T\).

The actual output torque of port \(O\) to port \(T\) is shown as follows:

\[ T_{OTr} = T_{OT} - \Delta T_{POT} - \Delta T_{VOT} \]  
(12)

\[ \Delta T_{POT} = \frac{C_m}{V_O} \]  
(13)

\[ \Delta T_{VOT} = \frac{C_m}{V_O} \]  
(14)

where \(\Delta T_{POT}\) is the friction torque loss caused by pressure. \(\Delta T_{VOT}\) is the frictional torque loss caused by medium viscosity.

### 3.3 Mathematical model of the pressure transformation ratio

When the four-port hydraulic transformer works steadily at a certain speed, the torque acting on the cylinder block by the oil at the four oil ports of the hydraulic transformer is balanced, which meets the following requirements:

\[ \lambda = \frac{\Delta P_{OT}}{\Delta P_{AB}} = \frac{1 - \frac{C_m}{V_O} \tan \frac{\theta}{2}}{1 + \frac{C_m}{V_O} \frac{1 + \tan^2(\theta/2)}{\Delta P_{AB}}} \]  
(15)

The core variable in (14) is the rotation speed of the cylinder block, the relation between the rotation speed and the actual flow of port \(B\) is as follows:

\[ Q_{B_b} = \omega V_B - \frac{C_m}{V_O} p_B \]  
(16)

The theoretical pressure transformation ratio of the four-port hydraulic transformer is obtained

\[ \lambda_{th} = \tan \frac{\theta}{2} = \frac{1 - \cos \theta}{1 + \cos \theta} \]  
(17)

### 4 Analysis of factors affecting the pressure transformation ratio

According to formula (14), the coefficient of the first item theoretical transformation ratio \(\tan^2(\theta/2)\) is \(<1\). It decreases with the increase of mechanical friction loss coefficient \(C_m\). In other words, when the control angle of valve plate is constant, the pressure transformation ratio decreases with the increase of mechanical friction loss coefficient. The viscous friction loss coefficient \(C_v\) and the laminar leakage coefficient \(C_l\) in the second term of (14) are on the numerator. It indicates that the pressure ratio decreases with the increase of viscous friction and laminar flow leakage, while recycling pressure difference \(\Delta P_{AB}\) is on the denominator, so the pressure ratio increases with the increase of recycling pressure difference. Based on the reference [17], the laminar flow leakage coefficient \(C_l = 3.3 \times 10^{-3}\), the viscous friction loss coefficient \(C_v = 206000\), the mechanical friction loss coefficient \(C_m = 0.076\), and the dynamic viscosity of working oil \(\mu = 0.03 \text{ Pa s}\), \(K = \pi z r \sin \beta\), where \(z = 7, r = 1.26 \times 10^{-2} \text{ m}, \beta = 40^\circ, A = 2.659 \times 10^{-4} \text{ m}^2\), i.e. \(K = 15 \text{ cm}^2\). According to the dimensional relationship, (14) and (16) of the pressure transformation ratio are simplified

\[ \lambda = 0.86 \times \frac{1 - \cos \theta}{1 + \cos \theta} - 1.91 \times 10^{-1} \times \frac{\omega}{(1 + \cos \theta) \Delta P_{AB}} \]  
(18)

\[ \lambda = \frac{\Delta P_{OT}}{\Delta P_{AB}} = 0.86 \tan \frac{\theta}{2} - 6.32 \times 10^{-1} \times \frac{1 + \tan^2(\theta/2)}{\Delta P_{AB}} \]  
(19)
4.1 Effect of low-pressure port B flow on the transformation ratio

To ensure the stability of the transformer characteristics, it is necessary to study the interfering factors of the transformation ratio. One of the most important interfering factors is cylinder speed. To analyse the influence of the rotational speed on the pressure transformation ratio, the partial derivation of (14) with respect to the rotational speed is shown as follows:

\[
\frac{\partial \lambda}{\partial \omega} = -\frac{C_{V\mu}}{\Delta p_{AB}} \cdot \frac{1 + \tan^2(\theta/2)}{\Delta p_{AB}}
\]  

It can be known from (20) that \( \frac{\partial \lambda}{\partial \omega} < 0 \). Hence, if other parameters remain unchanged, the increase of the cylinder rotational speed leads to the reduction of the transformation ratio. The simulation curve of the relationships between the rotational speed, control angle of the valve plate, and the pressure transformation ratio of the four-port hydraulic transformer is shown in Fig. 5a, and the simulation parameters were \( p_A = 20 \text{ MPa} \) and \( p_B = 10 \text{ MPa} \). According to Fig. 5a, when the valve plate angle is...
unchanged, the transformation ratio of the hydraulic transformer decreases with the cylinder rotational speed. The reason is that when the control angle of the valve plate is constant, the loss of the viscous friction torque increases with the increase of the cylinder rotational speed, which leads to the decrease of the transformation ratio. The transformation ratio curve with the actual flow rate of port B and the control angle of the valve plate as variables under the same conditions is shown in Fig. 5b. By comparing Figs. 5a and b, it can be seen that the influence trend of the output flow on the transformation ratio is basically consistent with that of the cylinder rotational speed. The reason is that when the control angle of the valve plate is constant, the output flow rate is close to a linear relationship with the cylinder rotational speed.

The simulation curve of the relationships between the control angle of the valve plate, the output flow rate, and the pressure transformation ratio of the four-port hydraulic transformer is shown in Fig. 6. It can be known from (21) that \(\partial \lambda / \partial \Delta p_{AB} > 0\). Therefore, when other parameters remain unchanged, the increase of the recycling pressure difference of the hydraulic transformer will increase the pressure transformation ratio, as shown in Fig. 6. When the transformation ratio is relatively small, the recycling pressure difference has a great influence on it. This is because when the pressure transformation ratio is small, the first term in (14) is small, and the effect of recycling pressure difference in the second item on the transformation ratio is significant relative to the first term. When the recycling pressure difference increases, the influence on the transformation ratio becomes smaller, the reason is that when recycling pressure difference is large, the first term in (14) is large, and the recycling pressure difference in the second item is on the denominator, so the influence on the transformation ratio is small relative to the first item.

4.3 Effect of oil viscosity on the pressure transformation ratio

During the operation of the four-port hydraulic transformer, the temperature of the oil changes greatly, and the viscosity of the oil also changes greatly. It is also important to analyse the influence of the oil on the pressure transformation ratio characteristics. The partial derivation of (14) with respect to the oil viscosity is shown as follows:

\[
\frac{\partial \lambda}{\partial \mu} = \frac{C_{\lambda} \tan (\theta/2) \lambda}{(1 + C_{\mu}) \Delta p_{AB}}
\]  

(22)

It can be known from (22) that \(\partial \lambda / \partial \mu < 0\), therefore, under the condition that other parameters remain unchanged, the decrease of the oil viscosity will increase the pressure transformation ratio. The effect of oil viscosity on the pressure ratio is shown in Fig. 7. The simulation parameters were \(p_A = 20\ MPa\), \(p_B = 10\ MPa\), and \(n = 1000\ r/min\). It can be seen from Fig. 7 that when the control angle of the valve plate is constant, the viscosity is reduced, so that the transformation ratio of the hydraulic transformer is increased.

5 Conclusion

A four-port hydraulic transformer with variable kidney-shaped holes is proposed, and its pressure transformation ratio characteristics are studied. The influence characteristics of low-pressure oil inlet flow, recycling pressure difference, and oil viscosity on the pressure transformation ratio are analysed. 

The main conclusions are as follows:

(i) The hydraulic transformer with variable kidney-shaped holes has four inlet and outlet oil ports. Theoretically, the flow rate of port A is the same as port B, the combination of ports A and B is equivalent to a hydraulic motor, and the flow rate of port T is the same as port O, and the combination of port T and O is equivalent to a hydraulic pump. The kidney-shaped hole of A and B on the valve plate has the same shape and size of T and O. The control angle of the valve plate can be adjusted to change the length of the kidney-shaped hole, and then change the pressure ratio. In this process, the flow of port A and port B does not change.

(ii) The four kidney-shaped holes do not cross the TDC and BDC, which avoids the phenomenon of oil absorption and drainage in plungers connected to the same kidney-shaped hole. In addition, the corresponding oil ports on the distributor cover and balanced cover are connected through the external oil circuit, which makes the value of the torque produced by the oil to the balanced valve plate is the same as the torque produced by the distributor plate, while in the opposite direction so that the oil does not produce torque to the valve plate shaft.
(iii) Theoretically, when the control angle of the valve plate is equal to 0, the displacement of port $A$ is 0, the displacement of port $O$ is the largest, and the pressure transformation ratio of the four-port hydraulic transformer is 0. When the control angle of the valve plate is equal to 90°, the displacement of port $A$ is the same as the displacement of port $O$, and the pressure transformation ratio of the four-port hydraulic transformer is 1. When the control angle of the valve plate is equal to 180°, the displacement of port $A$ is the largest, the displacement of port $O$ is 0, and the pressure transformation ratio of the four-port hydraulic transformer is the largest.

(iv) Since $\frac{\partial \lambda}{\partial \omega} < 0$, when the other parameters are unchanged, the increment of the rotational speed results in decreasing the transformation ratio. Since $\frac{\partial \lambda}{\partial \Delta p_{AB}} > 0$, when the other parameters are unchanged, the increment of the recycling pressure difference will increase the pressure transformation ratio, and when the transformation ratio is relatively small, the recycling pressure difference has a great influence on it. Since $\frac{\partial \lambda}{\partial \mu} < 0$, when the other parameters are unchanged, the decrease in viscosity leads to an increase in the pressure transformation ratio.

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