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Numerical research on hydrodynamic characteristics of end cover of pressure exchanger

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Abstract. To investigate hydrodynamic performance of the end cover under different inclined angles, a series of 3-Dimensional geometric models of the end cover with different inclined angles were built by Creo. The maximum inclined angle is 32 degrees and the minimum is 6 degrees. Numerical simulations by solving the Navier-Stokes equation, coupled with the “k-ε” turbulence model, were carried out. At last, regressive analysis method is used to deal with the result data. The data obtained by simulation were mainly analysed from three aspects. They are cause of the driving torque, drive efficiency and inclined angle of flow channel. The results show that the driving torque is formed mainly by the positive pressure of the water, and the influence of the viscous force on the driving torque of the rotor is negligible. What’s more, both driving torque and pressure difference decrease with the increase of inclined angle in the form of power function. The driving efficiency increases in form of logarithmic function with the increase of inclined angle. This research has a great significance in the control of rotational speed of rotor and revealed the relationship between the driving torque of the rotor and the flow channel of the end cover.

1. Introduction

A rotary pressure exchanger which is based on the positive displacement principle is a kind of fluid energy recovery equipment [1] [2]. It is one of the three core components of seawater desalination industry. Its operating principle is illustrated by Figure 1-1[1]. The key components of RPE include a rotor with axial ducts arranged in a circle around a centre tension rod, two end covers and one sleeve. In the work process, the fluid will generate a term of tangential velocity after it passed through the inclined flow channels and the rotor rotated in the sleeve is driven by this fluid.
Figure 1. structure view of the rotary pressure exchanger

Low pressure and high pressure brine will directly contact with each other and the pressure energy is transferred directly from the high pressure reject stream to a feed stream with no intervening walls. The pressurized seawater is discharged into lift pump. The pressure of brine decreased and then it is discharged by the feed stream.

The most important three features of pressure exchanger are flow-driven rotation, self-lubricating bearing and pressure transition control [3]. Now the latter two issues have been searched by many people. For example, Zhao Fei and his collaborators have carried out a detailed analysis on the problem of self-lubricating bearing [4]. They researched the support mechanism and stiffness of axial film in rotary pressure exchanger and revealed how much the clearness between cover and rotor should be to guarantee that the rotor can be supported by water and the leakage is maintained at a low level. Another important research was carried out by Yihui Zhou [5] and her partners, which revealed that the rotor speed is very important to control the maximum flow-in length and guarantee that the mixing is maintained at a low level. Many other studies show that the rotor speed has a great effect on the performance of pressure exchanger [6]. So the mechanism and characteristics of flow-driven is a problem we can’t avoid to guarantee the rotor rotates at ideal speed. But no detailed research on the problem of flow-driven has been carried out at present. In order to figure out the mechanism and characteristics of the flow-driven of pressure exchanger, a lot of work has been done in this paper.

The structure of the article is arranged as follows. Section 2 gives a detailed introduction of the research problem, in which geometry specifications and operating parameters are listed. Section 3 describes the numerical setup detailed. Section 4 presents the numerical results, including the velocity vectors at different inclined angles as well as the whole hydraulic moment analysis, followed by the conclusion in Section 5.

2. Description of problem

The section at the flow channel of the end cover is shown in figure 2-1. A term of tangential velocity will generate after the fluid passed through the inclined flow channel. Then the fluid produce a tangential impact on rotor so as to drive the rotor rotates in the sleeve.

From the qualitative point, bigger inclined angle means that more fluid with tangential velocity component drives the rotor, but the tangential velocity will be smaller. So the ultimate driving torque may be not larger than that in smaller inclined angle. It becomes important to get the change law between driving torque and inclined angle.

Figure 2. section view at flow channel of the end cover

In order to figure out that problem, a series of flow channels with different inclined angles are build. The inclined angles varies from 6 degrees to 32 degrees with 2 interval degrees. The geometry of flow channel with maximum inclined angle and minimum inclined angle are shown as figure 2-2 and figure 2-3 respectively.
In order to study the effect of inclined angle on driving torque, the volume flow rate is set to 70 m³/h, pressure at high pressure outlet is set to 6 MPa and that at low pressure outlet is set to 0.4 MPa. In addition, the rotor speed is set to be same.

3. Numerical simulation

3.1. Mesh Generation

The geometry model of the pressure exchanger was established by the commercial software—Creo. It includes two end covers and a rotor. The main geometry parameters are listed in Table 3-1 and the whole configuration can be seen in Figure 3-1.
end cover. Mesh independent verification is carried out to eliminate the effect of mesh size on computation results. The mesh of rotor and cover is shown in figure 3-2 and figure 3-3.

The number of mesh element of rotor reached 4 million and that of end cover reached 3.5 million. The quality of mesh of all parts are higher than 0.5. After computational test, it is proved that the mesh system can satisfy the requirement of the k-ε turbulence model and enhanced wall treatment, which can be seen from the y+ values on the walls of rotor and end cover displayed in Figures 3-4 and 3-5, respectively. At last, all the meshes are transferred from ICEMCD to fluent to compose an integral mesh. Interface is used to connect the mesh of different fluid zones.
3.2. **Boundary condition**

3.2.1. **Inlet boundary conditions.** The velocity inlet at inlet of end cover is used, whose magnitude is assumed to be uniform and determined by the experiment. The turbulence parameters are specified in terms of turbulence intensity and hydraulic diameter of the inlet.

3.2.2. **Outlet boundary conditions.** Pressure outlet is used at outlet of end cover, static pressure (p=0.4MPa) is specified for low pressure outlet and static pressure (p=6MPa) is specified for high pressure outlet. The turbulence parameters are specified in terms of turbulence intensity and hydraulic diameter of the inlet.

3.2.3. **Other conditions.** No-slip condition is assumed on all the solid walls, and enhanced wall treatment function is used to calculate the turbulence kinetic energy and turbulence dispersion frequency near the wall. The rotation of rotor domain is considered by the use of the multiple rotating reference frame (MRF) method.

3.3. **Solution strategy**

FLUENT is used to carry out the numerical simulations. The code solves the Reynolds averaged Navier–Stokes equations in a primitive variable form. The effects of turbulence are modelled using the k-ε turbulence in the simulation. The second-order upwind scheme is used for discretization of convective term and the second-order central difference scheme for discretization of diffusion term. The separated solver is used to solve the incompressible flow. Numerical convergence absolute criteria is set to a maximum of $1 \times 10^{-4}$.

4. **Results and discussions**

4.1. **Driving torque characteristics of pressure exchanger**

![Image of turbulent Reynolds number contour](image-url)
The rotor rotates clockwise under the driving of the water flow. The Upstream face and Downstream face of rotor are shown in figure 4-1. When the water flow shots to the Upstream face of rotor channels with a certain inclined angle, the kinetic energy of water flow is converted into the static pressure energy. So the pressure of Upstream face will rise, therefore a pressure difference will formed between the Upstream face and Downstream face. It is can be seen from the pressure distribution of the cross section of the rotor shown in figure 4-2.

For the sake of clearness, the range of displayed pressure is set as 5.85MPa to 6.35MPa, which is suitable for displaying the pressure distribution of high pressure side. It is can be seen from figure 4-2 that the inclined angle is smaller, the pressure difference between the Upstream face and Downstream face is larger. It indicates that the driving torque obtained by rotor is greater at smaller inclined angle.
According to the different forming mechanism, the hydrodynamic force acting on any objects can be divided into positive pressure and viscous shear force. The performance characteristics of that two kinds of force is also completely different. So the driving torque of rotor is divided into two parts in this paper. They are respectively called pressure torque caused by positive pressure and viscosity torque caused by viscous shear force. The trend of pressure torque denoted by $M_p$ along with the change of inclined angle denoted by $\theta$ is shown in figure 4-3. From that figure we can know that the pressure torque at any inclined angle is positive, which suggests that the water’s positive pressure is driving the rotor to rotate. The trend of pressure torque is obviously. The inclined angle is larger, the smaller the pressure torque. Especially when the inclined angle is small than 16°, the pressure torque decreased rapidly. Another characteristic is that the distribution of data points is regularly, roughly on a curve. Regression method is used to analyse these data and power function is used to fit these data points shown in figure 4-1. The regressive curve equation got from regressive analysis is

$$y = 130 \times x^{-0.757}$$  \hspace{1cm} (1)

Where $y$ represents the pressure torque and $x$ represents the inclined angle. The fitting degree index $R^2$ reached 0.9961.
The distribution of viscosity torque denoted by $M_v$ at every inclined angle is shown in figure 4-4. It is obviously that the viscosity torque at every inclined angle is negative, which suggests that the viscosity torque caused by viscous shear force hinders the rotation of rotor. But the absolute value of viscosity torque is very small. The biggest absolute value of torque caused by viscosity shear force is only $0.108(n*m)$ at the inclined angle of 6 degree. However the torque caused by positive pressure at that inclined angle is $28.7(n*m)$, which is much larger than viscosity torque. Although the distribution of data points of viscosity torque is not as regular as pressure torque, regressive analysis is carried out on the viscosity torque and linear function is used to fit these data points shown in figure 4-4. The linear regressive curve equation is

$$y = 0.0014x - 0.1034$$  \hspace{1cm} (2)

Where $y$ represents the viscosity torque and $x$ represents the inclined angle. The fitting degree index $R^2$ is 0.748.
Total torque denoted by $Mt$ is the sum of pressure torque and viscosity torque. Because the absolute value of viscosity torque is too small to influence the variation trend of total torque, the distribution of data points of total torque shown in figure 4-5 is very similar to the distribution of data points of pressure torque. Similarly, regressive analysis is carried out on the total torque and the regressive curve equation is

$$y = 130 \times x^{-0.79}$$

(3)

Where $y$ represents the total torque and $x$ represents the inclined angle. The fitting degree index $R^2$ is 0.996.

4.2. Pressure difference characteristics of pressure exchanger

The previous analysis shows that when water flows through the pressure exchanger, the water will produce a driving torque to drive the rotor to rotate. From the view of conservation of energy law, the water flow must have some loss of energy of itself. This can be confirmed from the pressure difference between the inlet and outlet. The pressure at high pressure inlet, high pressure outlet, low pressure inlet, low pressure outlet are denoted by $HP_{in}$, $HP_{out}$, $LP_{in}$, $LP_{out}$ respectively. So the total pressure difference can be described as follows.

$$PD = HP_{in} - HP_{out} + LP_{in} - LP_{out}$$

(4)

Where $PD$ represents the total pressure difference, which reflects the energy loss of water flow. The distribution of date points of pressure difference is shown in figure 4-6. It is obviously that the distribution of pressure difference and total torque is very similar, which suggests that larger total torque means larger pressure difference. Regressive analysis is also carried out on the pressure difference and the regressive curve equation is

$$y = 57.222 \times x^{-1.214}$$

(5)

Where $y$ represents the pressure difference and $x$ represents the inclined angle. The fitting degree index $R^2$ is 0.9969.
4.3. Driving efficiency characteristics of pressure exchanger

Total pressure difference between inlet and outlet represents the energy loss of water flow. Total driving torque is the output of water flow. So the driving efficiency is defined as the ratio of total driving torque and total pressure difference, which is described as follows.

$$\eta = \frac{M_t}{PD}$$  \hspace{1cm} (6)

Where $\eta$ represents the driving efficiency, $M_t$ represents the pressure torque, $PD$ represents the pressure difference. The distribution of driving efficiency denoted by $\eta$ at every inclined angle is shown in figure 4-7. It is obviously that the driving efficiency increased gradually with the increase of inclined angle, which is contrary to the trend of total torque and pressure difference. Logarithm curve is used to fit the data points of driving efficiency and the regressive curve equation got from regressive analysis is

$$y = 0.4851\ln(x) - 0.3378$$  \hspace{1cm} (7)

Where $y$ represents the driving efficiency and $x$ represents the inclined angle. The fitting degree index $R^2$ is 0.9924.
The isosurface of turbulence kinetic energy is shown in figure 4-8. The value of ISO is $5 \text{ J/kg}$, which indicates that the turbulence kinetic energy in the region coated by isosurface is Greater than or equal to $5 \text{ J/kg}$.
When water flows into channels of rotor, the water flow shots to the walls of rotor channels with a certain inclined angle. So the water flow is disordered by rotor and a large amount of vortex generated in this region. When the water flow into the end cover’s channel from the channels of rotor, the direction of water flow is changed. When $\theta<20^\circ$, the water flow is disordered seriously and a large amount of vortex generated in the channels of low pressure outlet and high pressure outlet. It is can be seen from figure 4-8 that the inclined angle $\theta$ is larger, the region where the turbulence kinetic energy is greater or equal to 5 J/kg is smaller, which indicates that the greater the inclined angle, the less energy of water flow dissipates into the turbulence. For the sake of clearness, the total energy loss of water flow, energy of driving rotor to rotate, energy dissipates into the turbulence are denoted by $E_t$, $E_d$ and $E_w$. So the following equation is established

$$E_t = E_d + E_w$$

(8)
It is known that the energy of driving rotor to rotate is what we want but the energy dissipates into the turbulence has no use for us. $E_w$ is smaller means the less useless energy generated, which suggests that the driving efficiency is higher. It is can be confirmed in figure 4-5.

5. Conclusion

Though flow simulation and analysis on the end cover under different inclined angles, the following conclusions are drawn.
1. k-ε turbulence model is capable of capturing the detailed information of the fluid flow and can be used to predict the driving torque of rotor under different inclined angles.
2. The total driving torque is composed of pressure torque and viscosity torque, in which the pressure torque is positive and the viscous torque is negative. Pressure torque is the main component of total torque. The influence of viscosity torque is negligible.
3. Both driving torque and pressure difference decrease with the increase of inclined angle in the form of power function. The regression equations were shown in equation (3) and (5) respectively.
4. The driving efficiency increases in form of logarithmic function with the increase of inclined angle. The regression equation is shown in equation (7).

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Nomenclature

- $\theta$: Inclined angle
- $M_v$: Driving torque caused by viscosity
- $M_p$: Driving torque caused by pressure
- $M_t$: Total driving torque
- $H_{Pin}$: Pressure at High pressure inlet
- $H_{Pout}$: Pressure at High pressure outlet
- $L_{Pin}$: Pressure at Low pressure inlet
- $L_{Pout}$: Pressure at Low pressure outlet
- $P_D$: Pressure difference
- $\eta$: Driving efficiency
- $E_t$: Total energy loss of water flow
- $E_d$: Energy of driving rotor to rotate
- $E_w$: Energy dissipates into the turbulence

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