Numerical Simulation of Flow Characteristics of Vortex Diode with Multi-tangential Tubes

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Abstract. By increasing the number of tangential tubes, the structure of the traditional vortex diode is changed to improve its performance parameters. Three kinds of vortex diodes with different number of tangential tubes are designed: double tangential tubes, three tangential tubes and four tangential tubes. Fluent is adopted for numerical simulation. With the increase of the number of tangential tubes, the forward and backward resistance coefficients decrease gradually, and the impedance ratio of the comprehensive performance parameters is related to the Reynolds number. In the case of low Reynolds number, the impedance ratios of vortex diodes of the double, triple and quadruple types of structures have little difference. In the case of high Reynolds number, the impedance ratios of vortex diodes of the three types of structures have different degree of improvement, compared with those of the vortex diode with single-tangential tube. The impedance ratio of the four tangential tubes is the highest, which is increased by about 7 times, that of the three tangential tubes is next, which is increased by about 3 times, and that of the double tangential tubes is increased by about 1 times.

1. Introduction
Fluid diode has different flow resistance in different flow direction, as a fluid control component, which plays the role of stopping valve. There are no mechanical rotating parts, mechanical fatigue and lubrication problems in the structure of the fluid diode, which has a very small probability of mechanical failure[1]. As a type of fluid diode, vortex diode has the advantages of small size and large difference in positive and negative flow resistance compared with other fluid diodes. In the 1980s, vortex diode began to be used in the post-treatment fuel transportation of the nuclear industry [2]. The flow characteristics of vortex diode is as follows: in the reverse flow, a strong swirling flow structure can be formed in the central region, with a high flow resistance, while in the forward flow, the flow is relatively simple and the flow resistance is much smaller. The concept of vortex diode was first proposed by Zobel[1], and its structure consists of three parts: axial tube, chamber and tangential tube. In order to improve the performance parameters of vortex diode, some optimization schemes have been made for its structure. Kulkarni et al. [3] carried out numerical and experimental studies on axial and tangential tubes, and Chinese scholars Yanhua Guo et al. [4] and Leqin Wang et al. [5, 6] optimized the structure of vortex diode and improved the performance of vortex diode. The structure of vortex diode was improved by increasing the number of tangential tubes. The double tangential tubes, three tangential tubes and four tangential tubes were designed respectively. The influence of the structure of multi-tangential tubes on the performance parameters of vortex diode was studied by numerical simulation.
2. Vortex diode and multi-tangential tubes type

2.1. Working mechanism and performance parameters of vortex diode

Vortex diode structure diagram is as shown in figure 1. In the case of reverse flow, the fluid enters the chamber through tangential tube jet flow. Under the constraint of the wall surface, the fluid spirals continuously to the center through the annular acceleration mode and finally forms a strong cyclone structure near the center of the chamber. Under the constraint of the wall surface, the strong swirl structure is formed near the center of the chamber after continuous precession through the annular acceleration mode. The strong swirling flow at the center is the main source of flow resistance and has extremely high pressure gradient. When the flow is positive, the fluid flows into the chamber from the axial tube and out from the tangential tube. The pressure gradient of the whole flow field is small, the flow is relatively simple and the flow resistance is small.

Figure 1. Vortex diode

Based on the theory of non-viscosity and combined with the flow field characteristics of the vortex diode, Wilkson J[7] deduced the positive and negative resistance coefficient (euler number Eu) of the vortex diode, which represents the one-way obstruction performance parameters, and the overall performance parameter impedance ratio $\varepsilon$. These three parameters become important parameters to measure the performance of vortex diodes. The equation of the flow resistance coefficient and the overall performance parameter impedance ratio are shown below:

$$\rho = \frac{\Delta P}{uP^2}$$

$$\varepsilon = \frac{Eu}{Eu}$$

2.2. Multi-tangential tube vortex diode

The diameter of inlet and outlet tubes of the classical Zobel vortex diode is the same. The ratio of the chamber diameter to the diameter of inlet and outlet tubes is about 6, and the impedance ratio is the largest. A single tangential tube of the vortex diode is designed into multi-tangential tubes to improve the performance parameters. Fig. 2 shows the geometric structure of the vortex diode with double tangential tube type, three tangential tube type and four tangential tube type. The diameter of the tube is 25mm and the ratio remains unchanged at 6.
2.3. Numerical method

The model grid division is carried out in ICEM software with tetrahedral grid and prismatic grid at the wall surface. The number of grids is about 800,000 and the quality of grids is above 0.4, as shown in figure 3. FLUENT software was used for numerical calculation of each model.

According to the existing studies, RNG k-e turbulence model [10] and RSM model [11] are mainly adopted for the swirl problem, in which RNG k-e turbulence model makes a swirling correction on the standard k-e turbulence model, but cannot accurately predict the strong swirl process. The RSM model directly modulates the Reynolds stress term and has higher precision for the strong swirl problem. Due to the existence of strong swirl structure in the reverse flow, the RSM model was selected as the reverse flow calculation model.

The inlet boundary conditions of positive and negative flow are set as velocity inlet conditions. Pressure base solver is adopted for calculation, and steady flow is adopted. PRESTO is adopted for discrete pressure term, SIMPLE algorithm is adopted for pressure velocity coupling, water is used as fluid working medium, and the mass outlet flow rate remains basically unchanged as the basis for convergence.

3. Analysis of calculation results

3.1. Positive and negative flow characteristics of vortex diode with multi-tangential tubes

In order to ensure the same Reynolds number, the mass flow rate of all kinds of vortex diodes is set to be the same. Fig. 4 is the forward flow diagram of each type of vortex diode. The fluid working medium flows into the chamber from the axial tube, and finally flows out from the tangential tube. The flow line is smooth, and the increased tangential tube can play the role of diversion. Fig. 5 is the flow diagram of the internal reverse flow of each type of vortex diode. The fluid working medium enters the chamber from tangential tube jet, and under the guidance of the annular wall surface, it...
continuously rotates and accelerates. Fig. 6 shows the pressure cloud diagram on the cross section of each type of vortex diode chamber when the flow is reversed. The chamber is divided into two regions. The peripheral annular area is the fluid acceleration area, and there is almost no pressure gradient in this area, and the flow resistance is relatively small. The internal circular area is a strong swirling flow structure, and the pressure gradient in this area increases obviously, which is the main part of the flow resistance. As the number of tangential tubes increases, the area of strong swirl structure gradually decreases and the area of acceleration area increases. This is because the increase in the number of tangential tubes leads to an inversely proportional decrease in the inlet flow rate. The more tributaries there are, the more time and space it takes for the confluence to form a strong swirling flow structure.

Figure 4. Flow diagram of positive flow inside each type of vortex diode
3.2. Comparative analysis of performance parameters

Fig. 7 shows the comparison of positive and negative resistance coefficients of various types of vortex diodes. In the case of forward flow, the increase of tangential tubes can well play the role of shunt, so that the stroke of fluid entering the chamber and then flowing to the tangential tube is greatly shortened, which reduces the chance of collision with the wall surface of the chamber and effectively reduces the forward flow resistance. In the case of reverse flow, according to the analysis of the pressure cloud diagram above, the increase of tangential tubes will weaken the reverse flow resistance. The most important parameter used to measure the performance of vortex diodes is the impedance ratio, Fig. 8 shows the impedance ratios of various vortex diodes. At low Reynolds number, the impedance ratios of vortex diodes differ little. With the increase of Reynolds number, the impedance ratio of multi-tangential tubes increases obviously, which shows that the larger the number of tangential tubes is, the greater the impedance ratio will be. This is because the weakening degree of forward flow resistance is much higher than that of reverse flow resistance.
Figure 7. Forward and backward resistance coefficients of each type of vortex diode

Figure 8. Impedance ratios of vortex diodes of various types

Fig. 9 is the velocity vector diagram on the cross section of various types of vortex diode Chamber in the forward flow under high Reynolds number. In the single tangential tube vortex diode, the fluid flows into the chamber from the axial tube and spreads out after colliding with the bottom of the chamber. In the double tangential tube vortex diode, an elliptical vortex field will be generated at the center to guide the flow direction. The fluid will no longer collide with the annular wall in a vertical way, and there will be a tangential component of the velocity, which weakens the head-on collision with the annular wall. In the triple tangential tubes vortex diode, the shape of the vortex field at the center is more circular, the guiding effect is strengthened, and the tangential component of velocity with the annular wall surface is further increased. In the four tangential tubes vortex diode, the guiding effect of the vortex field at the center is further enhanced, and the tangential component of the velocity of the annular wall dominates, making the fluid flow out of the chamber very smoothly. Meanwhile, with the increase of the number of tangential tubes, the area of the annular wall decreases, which will further reduces the probability of collision with the wall.
4. Summary
With the increase of the number of tangential tubes, the reverse resistance coefficient of vortex diodes decreases gradually, because the increase of tangential tubes requires more time and space to form a strong swirl structure. The positive resistance coefficient decreases simultaneously, because the multiple tangential tubes can play a good shunt guiding role. At low Reynolds number, the impedance ratios of double tangential tubes, triple tangential tubes and four tangential tubes have little difference. At high Reynolds number, the impedance ratio of the vortex diode's comprehensive performance parameters can be effectively improved. The more tangential tubes there are, the greater the improvement will be. The reduction degree of forward flow resistance is much higher than that of reverse flow resistance.

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