The resistance characteristics and intensifying cavitation effect of the vortex diodes

Chang Yang, Jiaxin Fang, Ke Cheng, Mengfei Shen, Yifan Zhou, Yawen Shu, Jian Wang*

School of Urban Construction, Wuhan University of Science and Technology, Wuhan, China

*Corresponding author e-mail: okwj@wust.edu.cn

Abstract

The vortex diode is an element that controls the unidirectional flow of the fluid, which is similar to the check valve. Because of its simple structure, no rotating parts, no external control and power, and high reliability, it is widely used in medical industry, nuclear industry, petrochemical industry and other industries. Based analyze the simulation results of the internal flow characteristics of the vortex diode.

Keywords

Eddy diode; impedance characteristics; bipolarity; structure optimization.

1. Introduction

The eddy current diode is increasingly valued as a device without rotating mechanical parts. At present, as a unidirectional flow element in fluid control, it has an important application value in fluid transmission, especially in the water hammer protection replacing the check valve. The typical structure of a vortex diode consists of three parts: a tangential tube, an axial tube, and a vortex chamber (as shown in Figure 1 (a)). When the fluid flows from the tangential pipe (reverse flow, Figure 1 (c)), a strong spiral flow is formed in the vortex chamber, creating high resistance, and when the fluid flow flows from the axial tube (forward flow, Figure 1 (b)), the flow resistance is small. Therefore, it can be regarded as a check valve, playing the role of the "diode" single guide in the circuit. The performance of the vortex diode is defined as the ratio of its reverse and forward resistance coefficient, that is, its performance ratio ε ($\varepsilon = \xi_R/\xi_F$).

Figure 1: Structure and working principle of the vortex diode

2. Study purpose and significance

With rapid development thanks to extensive investment in fossil energy and increasing reliance on energy, global energy demand is expected to grow by more than a third by 2035, with 60%

ISSN: 1813-4890

of the growth coming from developing countries. According to statistics, oil and natural gas resources will be declared exhausted in 2050, and coal resources will be exhausted in 150 years. The large-scale use of fossil fuels has also brought serious environmental pollution, leading to a series of problems such as the greenhouse effect and global warming. In addition to fossil fuels, there are many available energy sources, such as solar energy, wind energy, tidal energy and geothermal energy, etc., it is difficult to achieve large-scale industrial production and utilization of these energy sources in the near future due to technical problems and development costs. As a new type of energy, nuclear energy can not only replace the role of existing energy in the society and benefit mankind, but also has incomparable advantages compared with traditional energy and other new energy sources. The development of nuclear power in the future is an important direction for China to deal with the future energy crisis. Although the rapid development of nuclear power has made important contributions to promote the development of the world economy, but on the other hand, the nuclear power in safety, radioactive waste and spent fuel processing, nuclear proliferation also faces severe challenges, the history of three nuclear accidents, respectively is the 1979,1986, the Soviet chernobyl nuclear accident and fukushima nuclear accident in 2011, therefore to ensure the safety of nuclear reliability has become an important direction of the development of nuclear power in the future.

Nuclear spent fuel has the characteristics of high radioactivity in the processing process, the human body can not close contact, must ensure that the conveying device outside the biochemical wall of long distance stable operation, the fluid conveying equipment free maintenance in service, the country traditional non-mechanical conveying equipment (vacuum siphon device, vacuum tank lifting device, etc.) both from the transport capacity and safety and reliability can not meet the requirements, so it is necessary to develop a new type of safe and efficient fluid delivery system represented by vortex diode pump. Vortex diode pump is a kind of fluid delivery equipment, which is widely used in the nuclear spent fuel delivery system in the nuclear chemical industry.

3. Research status

Vortex diodes, a highly reliable check valve that can be used without requiring complete and immediate flow closure, have been practiced for decades. The main advantages of eddy current diodes over conventional alternatives are maintenance free, blockage resistant and corrosion resistant, reliable and well adapted for sterile and hazardous environments. The concept of eddy current diode has been proposed for many years, and its earliest structure was proposed by Tesla in 1920. In addition, in the history of vortex diode, Zobel first proposed the form of vortex diode in 1930. Since then, many scholars and research institutions at home and abroad have improved the geometric structure on the basis of Zobel vortex diode, whose purpose is to reduce the forward flow resistance as far as possible, increase the reverse flow resistance, so as to improve its unidirectional performance.

Compared with the check valve, the fluid diode has the advantages of high reliability, no mechanical rotating parts, and less affected by fatigue and corrosion. Therefore, it is widely used in medical, petrochemical, nuclear industry and many other fields. For example, the flexible diaphragm cavity vortex diode check valve used in cardiac surgery can effectively prevent blood return, and the vortex diode pump used in the nuclear industry can be operated, repaired and replaced over long distances, reducing the dose of radiation exposure to personnel. Compared with other types of fluid diodes, eddy current diodes have a longer history of use and research, simpler structure, higher reliability, and better performance.

The application of eddy current diodes in liquid lifting devices was proposed by BNFL. The advantage of the vortex diode pump is that the return of liquid in the discharge tube is greatly reduced. The decrease in reflux enables smaller bore storage containers and shorter cycle times.

For this way, we can use smaller piston barrels, longer lifting tubes and less amounts of liquid in each cycle. BNFL then proposed a secondary vortex diode pump device. The secondary vortex diode pump device can lift the liquid to a higher position with a lower pressure flushing pressure. The biggest advantage of the secondary vortex diode pump is that it greatly reduces the minimum low pressure impulse pressure required for lifting. For the same lift height, the lowest pressure impulse pressure required for the secondary vortex Dode pump is only half of the single vortex Dode pump.

At present, BNFL has a systematic research on vortex diode pump and applied to the delivery of high discharge solution in nuclear fuel reprocessing plant. However, BNFL's reports on the vortex diode pump device are published in the patent form, so we cannot obtain the experimental data on the design parameters and operation parameters of the vortex diode pump and the performance of the pump. At present, more research work on the vortex diode pump system is not reported, and few related research work has been carried out in China. So in order to apply the vortex diode pump, in nuclear power, nuclear fuel cycle, or the power nuclear technology application industry, we need to use FLUENT, according to the characteristics of the complete dynamic system operation, establish structure parameters and operating parameters, deduce the equation of device characteristics and the device efficiency factors into account optimization design theory.

4. Research content

4.1. Forward flow and reverse flow of the vortex diode

The eddy current diode consists of three parts: tangential tube, winding cavity and axial tube. Its working mode: when the fluid flows from the tangential tube into the chamber, due to the shrinkage of the tangential tube, the fluid working medium enters the vortex cavity as a jet under the action of the wall, resulting in large flow resistance, called reverse flow, the fluid flow is relatively simple, without large spiral, flow resistance is relatively small, which is called forward flow. The experimental analysis of the vortex diode is performed using a series of diode sizes and nozzle configurations. The analysis based on the Euler numbers of forward and backward flows helps to understand the contribution of different design parameters to diode performance. The design method for the vortex diode is proposed and verified.

4.2. Flow characteristics of different fluids in the vortex diodes

CFD simulation was used to obtain the flow field structure and velocity distribution using three different fluids. The results show that the experimental results using alternative fluids and water basically satisfy the scaling method, suggesting that experimental studies using alternative fluids are feasible to determine the flow characteristics of vortex diodes. The two dimensions obtained by the CFD simulation method are equivalent to those in the self-simulation region and those using different fluids, indicating that the established CFD simulation method can be used to calculate the two dimensions of vortex diodes. The flow field structure and velocity distribution of the reverse flow are independent of the fluid and only of the Reynolds number, suggesting the feasibility of experimental and CFD simulation studies of the dynamics of the vortex diode using alternative fluids.

4.3. Numerical simulation of eddy current diodes

Was analyzed with Kulkarni A A错误!未找到引用源。In this numerical simulation, it consists of a shrinking tangential tube, a vortex chamber with a chamfer, and a widening axial tube. The polyhedral mesh technique in FLUENT is applied to optimize the mesh. The total number of grids is more than 1 million, and the grid distortion is below 0.5. The division of the grid is shown in Figure 2. Apply F LUENT to calculate the forward and reverse streamline distribution and pressure distribution, as shown in Figure 3, Figure 4.

ISSN: 1813-4890

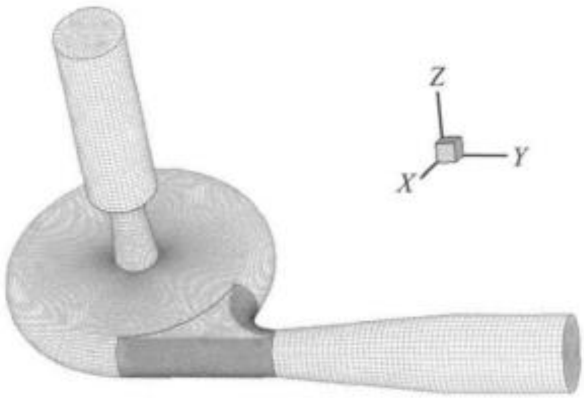


Figure 2: eddy diode grid division

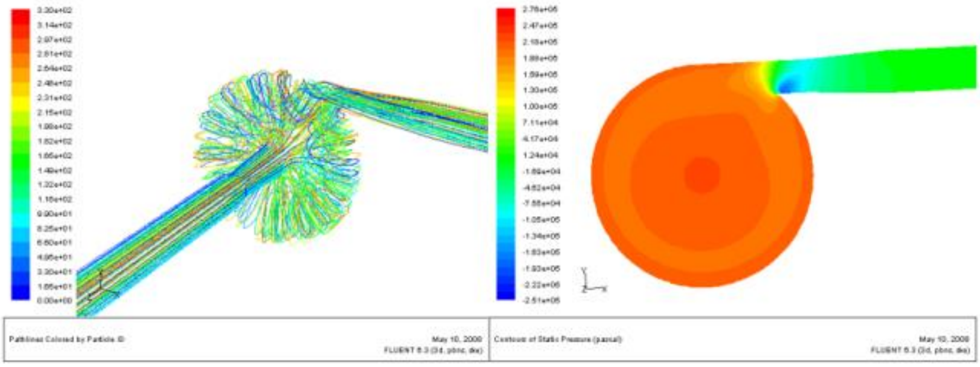
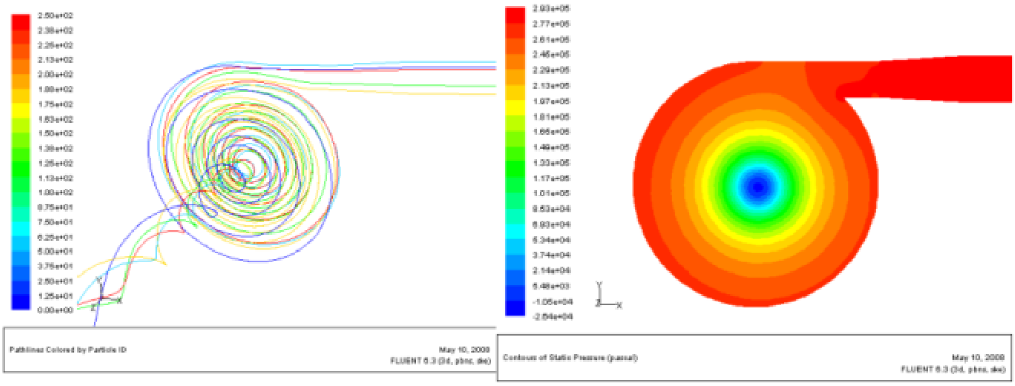


Figure 3: Forward flow line chart and pressure cloud map



(a) pathlines (b) contours of static pressure

Figure 4: reverse flow streamline chart and pressure cloud chart

For the vortex diode forward flow, the flow state is relatively simple and there is no strong spiral current, so the standard k- ε turbulence model can be simulated. For the reverse flow, the current flow is as strong as the fluid flow in the cyclone and hydrocyclone. Therefore, the simulation results of the cyclone and hydrocyclone can be used to guide the simulation of eddy current diode.

4.4. Introduction of the computing software

CFD, short for computational hydrodynamics, is a discretized mathematical method designed to solve the actual flow problem, using computer as a computing means to conduct numerical simulation of various mechanical and thermal problems involved in fluid flow to explore its internal laws. With the rapid doubling of computing power of computer technology in recent years, CFD also increasingly plays a more critical role in fluid analysis. Many fluid dynamic problems that are difficult to solve and cannot be solved in experimental research can be well solved by CFD. At present, CFD has gradually become a very important hydrodynamic analysis method besides theoretical analysis and experimental research.

Fluent Is developed by ANSYS company, currently used in the domestic and foreign widely a business CFD software package, suitable for most industrial process related to flow and heat transfer, its main advantage is advanced algorithm, internal integration has function perfect pre-processing and postprocessing module, many physical model, can be various complex flow problems, so in the vehicle, spacecraft wind resistance calculation, thermal power device and all kinds of fluid transport and other fields are common and in-depth application.

Fluent The general step of software to deal with fluid problems is grid division (pre-processing) -setting the flow mode and various simulation parameters-numerical calculation-calculation results after processing.

4.5. Analysis of the positive and negative resistance characteristics of the vortex diode

When the current in the vortex diode is flowing, the current is relatively smooth, but the water away from the tangential port flows to the tangential port in the chamber, and the water is vortex under the action of pressure difference and centrifugal force. A spin flow is produced. Theoretically, the reverse water loss in the vortex diode is mainly caused by three factors: the vortex flow of water flow in the vortex chamber, the vortex flow of water flow in the axial tube and the friction resistance of the tube wall. Shao forest For rough pipe wall (wall equivalent rough height of 100 um) and smooth pipe wall of the vortex diode under the same conditions, found that under the condition of the same import and export boundary, the reverse flow of rough pipe wall is about 45% more than smooth wall, friction resistance due to the rough wall is significantly less than the vortex volume of smooth wall, but it reduces the energy of water flow, water flow spiral motion is weakened, thus reducing the vortex volume in the chamber.

The numerical simulation increases the friction resistance of the tube wall of the vortex diode, which can prove that the water loss of the reverse flow of the vortex diode is mainly caused by the vortex flow. Increasing the friction resistance will reduce the strength of the vortex flow, so the reverse water loss of the vortex diode will decrease. Therefore, in order to increase the reverse resistance and optimize the vortex diode performance, the vortex flow strength in the vortex diode should be strengthened as far as possible.

5. Structural optimization of the vortex diodes

5.1. Decreases the asymmetry

The asymmetric structure of the vortex diode, the water of the tangent tube will squeeze the vortex, so that the vortex center deviates from the geometric center of the vortex chamber, which causes huge loss when the vortex flows from the chamber to the axial tube, and reduces the intensity of the vortex movement in the axial tube. Wang Leqin. Research by et al. showed that the center of the vortex will swing periodically, and this instability will cause periodic fluctuations of the pressure drop. The inconsistency of the vortex center and the vortex chamber center may be an important cause of this instability. So this asymmetry should be reduced in the design of the vortex diodes.

According to the formation of asymmetry, the circular vortex chamber can be changed into a spiral vortex chamber to reduce the influence of the vortex center and the vortex chamber center. The resistance coefficient of the spiral chamber, but the forward flow field.

5.2. Set the cone angle

Figure 5 shows the flow field of the front and rear vortex diode section. As can be seen from Figure 5 (a), in the case of forward flow, the water flow flows directly from the axial tube and collides directly into the lower wall of the vortex chamber. This will inevitably lead to most or complete loss of the kinetic energy of some water flow. Consider to add a conical cone Angle at the center of the bottom of the vortex cavity to divert the vertical fluid during the forward flow, so as to alleviate the impact of the fluid on the bottom of the vortex cavity, reduce the loss of water kinetic energy, and thus reduce the forward flow resistance. At the same time, in order to prevent the addition of a cone Angle to affect the reverse vortex flow, the connection between the axial tube and the vortex chamber is also chamferred, and the connection of the cone Angle at the bottom of the chamber and the vortex chamber is also increased, so as to minimize the influence of the narrowing of the flow channel in the vortex. See Figure Figure 5 (b).

Shao forest. The analysis of the front and posterior vortex diode forward resistance coefficient ξ by et al$_F$With the change of Reynolds number Re, it is found that the low low number will increase the water loss, but as the cone Angle increases with Re, the greater the resistance coefficient decreases. Because the vortex diode generally operates at high Reynolds number, this optimization has certain significance. Since the cone angle is set at the connection of the axial tube and the vortex chamber, the drag coefficient of the reverse flow is unchanged.

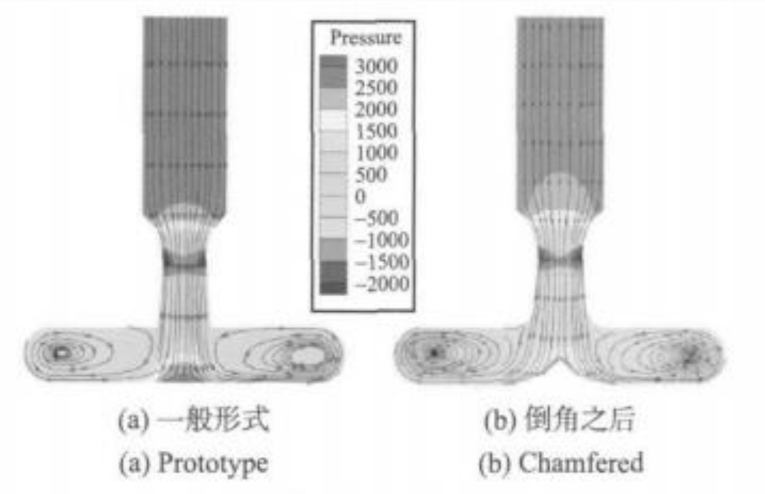


Figure 5: Cone, angular setting of the front and rear vortex diode section flow field

5.3. Optimal design of the tangential tube cone angle

In the traditional design of vortex diode, the tangential tube is generally designed as straight tube or conical, but the size of the cone angle is based on experience, and there is no specific optimization standard, and no research on its influence on the flow field. According to Jiao lei .Numerical simulation of tangential tube structure on the performance of vortex diode, they selected the tangential tube cone corner is 0° (straight type) and 3°, 50,7°, 10° five models, from the calculation of the tangential tube cone Angle on forward flow, reverse flow, the vortex diode $\boldsymbol{\varepsilon}$ value as the reference object, concluded that the vortex diode of tangential tube cone corner about 7° best, too small cone corner makes the reverse flow vortex strength is low, reverse resistance is small, too large cause reflux in the forward flow.

5.4. Appropriate cavity diameter ratio

The larger the cavity diameter ratio, the larger the reverse resistance coefficient, and the greater the impedance ratio. But according to the PJ Baker and BEAJacobs trials, such an inference is too simple and not consistent with the actual situation. Tippetts. It is considered that there is an optimal cavity diameter ratio for the vortex diode, which gives it the best comprehensive performance, where the classical Zobel structure is about 6.

6. The application of the vortex diodes

6.1. Application of flow diode in fluorine salt cooled high temperature reactor

When the normal operation of the reactor is perfunctory cooling, the heat taken away through the PRACS loop belongs to the heat loss of the system under the normal working conditions of the reactor, which will reduce the operation efficiency of the reactor. In order to reduce heat loss, it is necessary to limit the high temperature molten salt flow through the PHX heat exchanger under normal conditions, but under accident conditions, the coolant needs to flow through the PHX through the natural circulation process to export the decay heat of the core smoothly. To achieve this function, eddy current diodes are used in the PRACS loop of the reactor passive waste heat discharge system. Because of its simple structure, there are no moving parts, which reduces the probability of irregular shutdown due to mechanical failure. For the ideal vortex diode used in the PRACS loop, the flow through the PRACS loop should reach the minimum under normal conditions, and the flow through the natural forward loop should provide sufficient cooling capacity in accident conditions.

6.2. Eddy diodes are applied to cavitation in sewage treatment

The vortex diodes range from no return valves in the nuclear industry to cavitation and disinfection devices, and there is increasing interest in developing various sewage treatment schemes using vortex diode-based hydrodynamic cavitation techniques. For sewage treatment applications, vortical diodes are used in the so-called "reverse" configuration where the fluid enters the diode lumen from the tangential port, forming a vortex and passing through the axial port. Strong cyclone creates a low pressure zone in the center of the vortex, which extends to the axial port, leading to cavitation under certain conditions. These resulting cavities escape the diode through the axial port and collapse as they enter higher pressure regions. The cavity collapse realizes a local area of high shear, high temperature and high pressure. In these collapsed zones, the carbon – carbon bonds of certain organic pollutants can be resolved and macromolecules are resolved into micromolecules. Moreover, producing highly reactive free radicals, which can nonselectively oxidize contaminants.

7. The Future and Outlook

Since Zobel, it has been nearly a century since the development of nuclear spent fuel transmission system, but its research at home and abroad has not been perfect, and there is no comprehensive understanding of its internal working mechanism. Although the vortex diode has been gradually applied in all aspects, the internal flow field characteristics of the vortex diode need to be further studied, improve the stability measures of the reverse flow and further optimize the improvement of the vortex diode structure.

Acknowledgments

This work was financially supported by“Innovation and entrepreneurship training plan program for college students of Wuhan University of Science and Technology in 2022（22Z025）”and“Natural Science Foundation of Hubei Province（2021CFB495）”.

References

[1] OECD/EA WORLD ENERGY OUTLOOK 2012 [M] two thousand and twelve.

[2] Guo Yanhua Experimental Study on the Performance of Nuclear Pneumatic Pulsed Liquid Jet Pump and Eddy Current Diode Pump [D]. Tsinghua University, 2004.

[3] Kulkarni A A, Ranade V V, Rajeev R, et al. CFD Simulation of Flow in Vortex Diodes [J] Aiche Journal, 2008,54 (5): 1139-1152.

[4] John D.A. Introduction to computational fluid dynamics [M]. Beijing: Tsinghua University Press

[5] ANSYS FLUENT 14.0 User's Guide [M]. ANSYS Inc. 2011.

[6] Shao Linlin, Li Jiangyun, Qiu Han. Numerical simulation analysis of improving the performance of eddy current diodes [J]. Journal of Engineering Thermophysics, 2011,32 (06): 953-956.

[7] Wang Leqin, Yin Junlian, Sun Qingjun, et al. Numerical simulation of the internal flow field of vortex diode pumps [J]. Fluid Machinery. 2009,37 (4): 25-28.

[8] Jiao Lei, Chen Zongnan, Wu Chunjie, Liu Jintao, Wang Leqin. Numerical simulation of the effect of tangential tube structure on the performance of eddy current diodes [J]. Journal of Engineering Thermophysics, 2011,32 (03): 415-418.

[9] Wilkson J, Motamed Amini A, I Owen Compressible and Confined Vortex Flow [J]. Heat and Fluid Flow, 1988,9 (4): 373-380.

[10] Tippetts J R, Priestman G H, Thompson D. Developments in Power Fluids for Application in Nuclear Plant [J] Transactions of the ASME, 1981103:342-350.

[11] Cao Yin Design optimization and experimental research of vortex diode [D]. Graduate School of Chinese Academy of Sciences (Shanghai Institute of Applied Physics), 2015.

[12] Design optimization and experimental study of Cao Yin vortex diodes [D] Graduate School of Chinese Academy of Sciences (Shanghai Institute of Appl.