Numerical Study on the Influence of Exhaust Structure on the Performance of a High Expansion Ratio Turbine

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Abstract. A numerical simulation study on the influence of downstream pipe on turbine performance and flow is carried out for a high expansion ratio steam turbine. The abrupt change of the flow channel leads to severe reverse flow and increased back pressure, thus reduce the steam turbine power. The loss in the cylindrical cavity is up to 82% of the total loss downstream the steam turbine. By using a branch pipe to exhaust the steam of the passages downstream the intake area, the blast loss and mixing loss are significantly reduced for the non-intake passage, resulting a total reduction of 30.3%, and the power is increased by 5.3%. It provides a reference for the subsequent optimization design of flow channel.

Keywords: High expansion ratio, steam turbine, exhaust pipe, loss, numerical simulation

1. Introduction

The power system is the main component of the underwater vehicle, which significantly affects the speed, range, depth, reliability and cost. The steam turbine engine, with the ability of increasing the speed of underwater vehicles, is one of the main development directions of underwater vehicle engines in the future. Because of high expansion ratio steam turbines have small size, light weight, large expansion ratio and high power. It has been widely used in underwater vehicle power systems[1].

The exhaust structure of the steam turbine changes the speed, pressure and other parameters of the air flow[2], affect the flow in the steam turbine runner, and then change the performance[3]. Li Yong[4] conducted a numerical simulation study on the last stage blade and exhaust cylinder of a certain type of steam turbine. It was found that the fluid flow in the last stage blade channel was greatly affected by the non-uniformity of the flow in the exhaust cylinder, and the flow and parameter distribution in the blade channel showed non-periodical. Chai Jiaxing[5] used numerical simulation methods to study the influence of intake and exhaust structures on the performance of steam turbines with large expansion ratios, and studies have shown that the flow separation and vortex structure in the exhaust structure have caused significant changes in the aerodynamic parameter distribution in the blade flow path, and
the efficiency of the steam turbine stage is decreased. Fan Tao[6] numerically analyzed the aerodynamic characteristics of the coupling of the last two stages of the steam turbine blades and the low-pressure exhaust cylinder, pointed out that the reasonable design of the few stages of blades is obtained with the influence of the exhaust cylinder.

The supersonic flow in the large expansion ratio steam turbine lead to a complex wave system, hence extremely complicated local flow situation[7,8], and its interaction with the rear exhaust structure will be more intense, especially for the local intake structure. The downstream structure has a greater impact on the turbine runner in the non-intake zone. Therefore, this paper conducts a joint simulation of the exhaust structure and a steam turbine with a large expansion ratio, reveals the influence of the exhaust structure on the performance of the steam turbine and the evolution of the loss in the pipeline, and conducts a preliminary discussion on structural improvements.

2. Research Objects and Numerical Methods

The large expansion ratio steam turbine studied in this paper is a single-stage axial flow steam turbine, with the oblique-cut laval nozzle. The stator blades bear most of the enthalpy drop. In order to ensure the nozzle size matching the moving blades, double-jet local air intake mode of turbine structure. In order to study the effect of the exhaust structure on the performance of the steam turbine with a large expansion ratio and the loss characteristics of the pipeline, two typical structures were studied, namely the outlet pipe connected to the rear of the cylindrical cavity and the pipeless structure. As shown in Fig.1, the entire calculation domain consists of four parts: double nozzles, steam turbine blade row, cylindrical cavity, and outlet pipe. The number of rotor blades is 36. Due to the system structural space limitation, the outlet nozzle adopts an eccentric arrangement.

The computational mesh is generated by the commercial solver ICEM. In order to ensure the quality of the grid, local grids are encrypted on the wall and structural mutation areas. The number of nozzle grids is about 300,000, and the turbine runner grid is about 4.8 million. The cavity grid is about 2 million, the outlet nozzle grid is about 600,000, the $y^+$ of the adjacent to the wall is distributed in the range of 20-50, and the total number of grids is 7.6 million.

Using CFX software for simulation calculation, the inlet working fluid is superheated steam, the boundary conditions are as follows: the total pressure of the nozzle inlet is 7.0MPa, the total
temperature is 793K; the given static pressure of the outlet nozzle is 0.15MPa. The rotor speed is 100,000 rpm, and the turbulence model is the k-ε model.

3. Calculation Results and Analysis

3.1 Flow and Loss Characteristics

Fig.3 shows the Mach number and three-dimensional streamline distribution in the flow channel from the nozzle inlet to the nozzle outlet.

![Fig. 3. Three-dimensional streamlines and Mach number distribution](image)

The flow from the annular into the cylindrical cavity after the exit of the steam turbine has a significant rotation speed. From the outlet of the steam turbine to the annular cylinder section, where the area of the flow channel increases sharply, the flow expands violently, forming an annular swirl structure in the cylindrical cavity. When the outlet of the cylindrical cavity is further connected to the nozzle, the area of the flow channel decreases sharply again, obstructing the fluid flow. The violently mixed and rotating airflow in the barrel section concentrates at the inlet of the nozzle, resulting in increased local Mach number and friction loss. In the nozzle, due to the uneven upstream velocity and pressure, plus the strong swirling flow, the streamlines in the pipe are with complex rotation and local back-flow characteristics, hence the internal mixing loss is relatively large.

Fig.4 shows the total pressure distribution at different sections of the steam turbine outlet and downstream. Because the steam turbine stage adopts the partial air intake form, the total pressure downstream of the working flow channel area corresponding to the inlet nozzle is relatively high, and the high total pressure airflow flows toward the outer wall surface due to centrifugal force. An the downstream of the non-working flow channel area, where there is mainly the reflux steam and the leakage one, the total pressure is relatively low.

At the interface between the downstream annular section of the steam turbine and the connecting section provided in Fig.4(b), the total pressure in some areas is relatively high, which can reach more than 90% of the average one at the exit section of the steam turbine, but the total pressure in some areas is relatively small, indicating that the pipe has a significant impact on the flow in the cylinder section. In turn it leads to the non-uniformity of the inlet of the nozzle, and it will inevitably increase the mixing loss of the airflow downstream. In the connecting section, the low is mixed along the flow direction, and the uniformity of the total pressure is improved. In addition, it can be seen from the total pressure distribution that there is still obvious swirling motion in the downstream flow and the flow in the high-energy zone of each cross section migrates along the circumferential position. Therefore, the swirling effect of the steam turbine outlet travels a long distance downstream, which has an important influence on the evolution and distribution of losses in each section of the flow passage.
3.2 Influence of Exhaust Nozzle Structure on Steam Turbine Performance

Based on the previous analysis, the outlet nozzle has an important influence, equivalent to that caused by partial discharging steam in the cylindrical cavity, on the flow in the outlet section of the steam turbine. There is obvious swirl and back-flow in the cylinder, which may affect the internal flow of the non-intake part of the turbine and its aerodynamic performance. Therefore, influences of exhaust nozzle structure on steam turbine performance are carried out in the section.

![Pressures in cylindrical cavity inlet and nozzle imports](image)

Fig. 4. Distribution of total pressure in different sections along the flow direction

The total power of the steam turbine with no export nozzle is 120.7 kW, while that with an export nozzle is 113.4 kW. Combined with the steam turbine outlet pressure distribution given in Fig. 5, when the outlet is taken over, the flow is blocked due to the partial discharging of the cylindrical cavity, making the turbine outlet pressure significantly higher than the direct exhaust to the environment.
which would affect local flow field. For the working area corresponding to the nozzle, because the downstream flow of the steam turbine is blocked and the pressure rises, the Mach number of the expansion section after the flow passage throat is significantly reduced, as shown in Fig.6.

![Fig. 6. Relative Mach number and streamline distribution of 50% span](image)

When there is an eccentric connection in the downstream, the high pressure in the cylindrical cavity aggravates the back-flow of the turbine runner in the non-intake area, which increases the blast loss and the repulsion loss when the part of the impeller entering the nozzle intake area during the rotation of the impeller. In addition, since the eccentric nozzle at the outlet of the cylindrical cavity is close to the outlet of the nozzle, the downstream steam in the nozzle far away the connection is severely blocked, so as to the local loss and backflow.

### 3.3 Researches on Improvement of Export Nozzle

Further researches on the structure improvement of the outlet nozzle are carried out. As shown in Fig.7, the improved type (Cas1) uses two branch pipes, corresponding to the outlets of the working wheels downstream of the two nozzles respectively, to replace the cylindrical section. The exhaust gas is collected and discharged downstream in the additional three-way structure.

![Fig. 7. Improved structure of connecting pipe](image)

Fig.8 provides the three-dimensional streamlines and Mach number distribution in the improved outlet nozzle. The nozzle downstream of the nozzle outlet area has a better collection effect on the turbine exhaust steam in the working area, and the backflow phenomenon in the non-working area is significantly weakened. Therefore, the blast loss of the steam turbine and the repelling loss when the steam turbine enters the nozzle outlet downstream is reduced. The leakage flow is slightly increased with the increased local Mach number.
In addition, the velocity of the steam at the turbine outlet has a large tangential component, combining with the nozzle perpendicular to the outlet annulus, and there is a large range of recirculation vortex area inside the additional three-way connection. Further optimization of such structure is required to reduce the flow loss in the downstream pipeline of the steam turbine and improve the system efficiency.

Fig. 9 shows the Mach number and streamlines distribution at the midspan. Compared with the primary structure, the three-way pipe connection structure is able to increase the steam Mach number at the downstream of the nozzle, and there is inevitably increase of local aerodynamic performance. In the non-intake area, because the turbine outlet is close to the wall, it is equivalent to reducing the outlet axial return gap, and only a small amount of air flow in the working area returns to the flow channel, thereby reducing the blast loss. The back-flow is weak, and the repelling loss of the runner rotating into the intake area must be small. Based on the above reasons, the power of the steam turbine significantly increases to 127.0 kW, which is 5.3% larger than that with the original prototype export nozzle structure and is also higher than the power when the downstream steam turbine has only a cylindrical cavity structure. Therefore, a reasonable design of the steam turbine outlet pipe structure can significantly improve the expansion capacity of the steam turbine in the intake zone and reduce the blast loss and repelling loss.

Change of the averaged total pressure along axial sections is drawn in Fig.10. The positions of the cross-sections are shown in Fig.7. The cross-section 1 is the turbine outlet, the cross-section 2 is located at the inlet of the prototype connector (Cas0) (equivalent to no connecting pipe structure at the outlet of
the cylindrical cavity), and the cross-section 3 corresponds to the downstream of the two gas collecting pipes of the improved type connecting pipe (Cas1). Due to the low outlet pressure of the cylindrical cavity, the steam turbine expands violently and the total pressure at section 1 without export nozzle (Ori) is lower than those of the other two cases. When the eccentric nozzle is installed directly downstream of the cylindrical cavity, the flow in the cylindrical cavity is blocked and the return flow is enhanced, which affects the expansion of the internal airflow of the steam turbine and the total pressure at the outlet of the steam turbine is higher (case 1). When the improved structure is adopted, the total pressure of the steam turbine outlet is between the first two structures. However, the improved steam turbine has the highest power, due to the reduction of the steam turbine stage blast and repelling loss mentioned above.

Fig. 10. Change of total pressure along axial sections

Fig. 11 provides difference the total pressure compared with the cross section 1, the turbine outlet. For the prototype nozzle structure (case 0), the total pressure loss between section 3 and section 1 is 145kPa, and the total pressure loss from the steam turbine outlet to the nozzle structure (or inside the cylindrical cavity) accounts for about 82% of the total loss of the steam turbine outlet. With improved nozzle structure, the total loss is reduced to 101kPa, which is 30.3% less than that with the prototype takeover structure. In the case without connection, the relative total pressure loss of section 2 is between the two connection structures. Therefore, the improved connecting pipe structure is beneficial to the exhaust of the steam turbine in the intake working area, and the loss of the downstream pipeline of the steam turbine is minimized.

Fig. 11. Total pressure loss along flow direction

4. Conclusions
Numerical simulations of the influence of downstream pipe on turbine performance and flow are carried out. And the following conclusions are drawn:
(1) The exhaust pipe structure of the steam turbine has an important influence on the power of the steam turbine. The cylindrical cavity connecting pipe structure blocks the flow at turbine outlet. There are complex back flow and swirling flow in the passage. Compared with the case without a nozzle, the power of the steam turbine is reduced by about 6%, and the downstream flow loss is significantly increased. In particular, the loss in the cylindrical cavity accounts for 82% of the total loss from the outlet of the steam turbine to the nozzle.

(2) The three-way structure could directly guide the exhaust flow in the intake zone, and it effectively reduces the blast loss and repelling loss of the steam turbine. The power is increased by 5.3% compared with the prototype connection structure, which is higher than that of the cylindrical cavity without a connection structure. The flow loss is reduced by 30.3% compared with the original structure.

References
[1] Zheng Zhifei, Shi Xiaofeng, Yi Yin, et al. Application and Development of Gas Turbine Engine in Torpedo Power System[J]. Torpedo Technology, 2006, 14(4): 11-15[in Chinese]
[2] Burton Z, Ingram G L, Hogg S. A Literature Review of Low Pressure Steam Turbine Exhaust Hood and Diffuser Studies[J]. Journal of Engineering for Gas Turbines and Power, 2013, 135(6): 062001-1-10
[3] Liu J J, Hynes T P. The Investigation of Turbine and Exhaust Interactions in Asymmetric Flows Blade-Row Models Applied[J]. Journal of Turbomachinery, 2003, 125(1): 121-127.
[4] Li Yong. Joint calculation and optimization modification of the last stage of high-power steam turbine low-pressure exhaust cylinder [D]. Harbin: Master's thesis of Harbin Institute of Technology, 2011.[in Chinese]
[5] Chai Jiaxing, Ma Guojun, Gao Jie, et al. Research on the influence of inlet and exhaust shells on the performance of full-flow steam turbines with large expansion ratios [J/OL]. Advance technology.[in Chinese]
[6] Fan Tao, Xie Yonghui, Zhang Di, et al. Three-dimensional numerical simulation of coupled flow between low pressure exhaust cylinder and last two stages of steam turbine[J]. Proceedings of the Chinese Society for Electrical Engineering. 2007, 27(26): 90-95[in Chinese]
[7] Liu Guangtao, Huang Hongyan, Wang Xiangfeng, et al. Research on calculation of three-dimensional unconstant constant value of large expansion ratio steam turbine[J]. Steam Turbine Technology. 2012, (6): 11-15[in Chinese]
[8] Yi Jinbao, Qian Jianping, Dong Chunpeng. Numerical study on the flow field and performance of the flow-through part of the steam turbine of an underwater vehicle[J]. Torpedo Technology, 2009, 17(4): 61-66[in Chinese]