

On-cam operating characteristics of draft tube of tubular turbine based on vortex field analysis

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Abstract

In order to improve the efficiency of water turbine and the stability of the unit,numerical simulation is carried out for the draft tube of tubular turbine,The evolution characteristics of the vortex belt under different working conditions and the variation rule of the enstrophy and pressure pulsation are obtained.The results show that the kinetic energy of the fluid is affected by the enstrophy, and the rotation vortex belt is related to the flow energy in the tail water flow path, so the rotation vortex belt is closely related to the enstrophy.With the increase of the draft tube guide vane opening, the vortex belt with obvious changes,when the guide vane opening is large, that is close to the on-cam operating condition, in the center of the tail water flow path shows a whole vortex runner,at that time the tail water energy recovery is the best.The efficiency of water turbine is the best.The trend of vortex energy and pressure pulsations shows the opposite variation, so there is a certain correlation between the enstrophy and the pressure pulsation.

1.Introduction

After years of development, high head hydropower resource has become less and less, while low head water resource is very rich, so the development of water resources gradually turns to the low head field. With this background, tubular turbines suitable for low head and large flow have received much attention. The internal flow of turbine is complex. The vortex and vortex belt of draft tube between blade and guide vane are the important causes of pressure pulsation. The low-frequency vibration caused by vortex belt of draft tube is more obvious^[1-3]. The study of draft tube pressure fluctuation is of great importance to the safe operation of the unit and the improvement of the working efficiency of the turbine.

Wu Yulin et al^[4] conducted unsteady three-dimensional numerical simulation of turbulence to the whole flow passage of hydraulic turbine and concluded the changing rules of variation of vortex flow in draft tube with time. By analyzing the change of vortex core radius of draft tube, periodic motion and axial velocity, and testing the effects of pressure fluctuation of tail pipe, researchers received the relationship between the pressure pulsation frequency and periodic vortex. He Chenglian et al^[5] have carried on the monitor to the pressure data of the turbine model under different working conditions. Through the FFT spectrum hydraulic pulsation data analysis, researchers received the variation laws of pressure pulsation inside the draft tube at different locations under different conditions in different time domain and frequency domain. Liao Weili et al^[6] have carried on the research, which has shown that under different opening degree, the vortex concentration in the draft tube is

different and the characteristics are different. Zheng Min et al^[7] applied the vapor-liquid mixed transportation homogeneous hypothesis and cavitation model based on component transport equation. By solving Reynolds averaged N-S equations with the vapor-liquid mixed homogeneous flow and the vapor component transport equation, and considering the influence of non-condensable vapor, researchers calculated the changing characteristics of the cavitation flow and pressure pulsation inside the tubular turbine tail water pipe. Based on large eddy, Xia Chenyu et al^[8] simulated the Smrgorinsky-Lilly dynamic subgrid model, conducted unsteady calculation on 7 different operating conditions of bulb turbine, and obtained pressure fluctuation information at the measuring point of the key position in the channel under each condition. Fu Jie et al^[9] used the large eddy simulation (LES) model of Fluent software to simulate the pressure pulsation of the draft tube of the tubular-Francis turbine, and combined with the numerical simulation of the vortex rope in draft tube, they provided solution to the vibration problem of water turbine. With bulb turbine in a hydropower station as the basis, Ma Xijin et al^[10] established three-dimensional geometric model, completed the transient calculation from the inlet to the outlet flow of the draft tube, received the pressure pulsation waveform, and used the FFT transform to get the pressure fluctuation spectrum, thus analyzing the bulb turbine pressure pulsation. Ji Jinting et al^[11] applied numerical simulation of 3D unsteady turbulent flow in the axial flow turbine flow as the basis, analyzed the unsteady flow field in the axial flow turbine draft tube, studied the form of the draft tube vortex and analyzed the amplitude and frequency characteristics of the pressure pulsation. Some scholars abroad have made much research on the tubular turbine, which have great guiding significance for our research^[12-18].

In this thesis, with the method of numerical simulation, under different working conditions, researchers conducted numerical calculation and analysis of the characteristics of the rotating vortex belts inside the draft tube, explored the causes, development and evolution process of formation for draft tube vortex rotation, and found out the relationship between the pressure fluctuation and vortex.

2. Energy equation analysis of draft tube

In this thesis, the effects of enstrophy on the dynamics of draft tube and the efficiency of turbine are studied, and the cause and evolution law of rotating vortex belt are analyzed. Enstrophy is an important concept in vortex dynamics. It is the dissipation of fluid viscosity and vorticity field to the kinetic energy of fluid, defined as scalar. Among them is vorticity, enstrophy not only has the spin characteristic of flow field, but also reflects the energy dissipation characteristic of fluid^[19-20].

The viscous dissipation function for incompressible fluids is mentioned in reference [19]:

$$\Phi=2\mu\left(\frac{\omega^2}{2}\right) \quad (1)$$

In the equation, Φ is viscous dissipation; ω is vorticity.

As mentioned in the literature [20], for an incompressible fluid, the kinetic equation can be expressed as:

$$\rho \frac{DE}{Dt} = -\nabla \cdot (pu) - \nabla(\mu_{eff} \omega \times u) - \mu_{eff} |\omega|^2 \quad (2)$$

In the equation: $\nabla \cdot (pu)$ is the role of surface forces; $\nabla(\mu_{eff} \omega \times u)$ is the performance of the nonlinear effect of the vorticity and velocity field in viscous fluid; $\mu_{eff} |\omega|^2$ is enstrophy.

In this thesis, the influence of enstrophy on the draft tube is studied, so the formula (2) can be simplified as follows by combining formula (1):

$$\rho \frac{DE}{Dt} = -\nabla \cdot (pu) - \nabla(\mu_{eff} \omega \times u) - \left(\frac{\omega^2}{2}\right) \quad (3)$$

By the formula (1) and (3) it can be seen that the viscous dissipation and enstrophy is proportional to the enstrophy increases. The larger the fluid kinetic energy attenuation, the more the part of mechanical energy in the tail pipe transform into heat energy, and the better effect of energy recovery of tail pipe. By the formula (3) we can see that the generation of rotating vortex is closely related to the distribution of energy in the tail pipes, the kinetic energy of the fluid tail pipe contains rotational kinetic energy of rotating vortex zone. Due to the enstrophy decay effect on fluid kinetic energy, the energy that maintains the rotation vortex motion is reduced. Under the circumstance of the lack of energy supply, the amount of rotating vortex gradually weakens or even disappears. Therefore, the relationship between enstrophy, draft tube vortex belt and pressure fluctuation is further studied in this thesis.

3. Numerical calculation of vorticity in on-cam operating condition

3.1 research subjects

This thesis selects the typical tubular turbine machine as the research object, the ratio of model and prototype is 1:1, the wheel diameter is $D1=7.2\text{m}$, the runner blade number is 4 and the guide vane number is 16, the turbine rated speed is 68t/min. The Pro/E 3D software is applied to conduct the 3D modeling, the model is shown in figure 1. The draft tube was calculated by using the software of ANSYS CFX14.5, the runner opening angle is 28° , the opening angles of the guide are 39° , 43° and 47° . The computational domain parameters are divided by the structural mesh and the unstructured mesh. The grid of three working conditions is shown in Figure 2. The number of grids is shown in table 1. RNG k- turbulence model is used and the flow entrance and outlet pressure are selected.

3.1.1 physical model. The tail pipe model used in this thesis is shown in Figure 1, and the model is composed of guide vane and runner and draft tube.



Figure. 1 Draft tube model

3.1.2 mesh generation. The tail pipe model is meshed, and the tail pipe is divided into hexahedral structured grids by using ICEM mesh software. As shown in Figure 2, the mesh parameters are shown in table 1.



Figure. 2 Draft tube mesh

Table 1 Draft tube grid parameters

name	node	unit
39 °	1295527	6956311
43 °	1298243	7156875
47 °	1306523	7346423

3.2 numerical analysis

In the numerical calculation, the unsteady turbulent flow calculations are conducted under the condition of 28° in selected wheel opening; 39°, 43° and 47° of the three working conditions of the opening of the guide. As shown in Figure 3, the 3 pressure pulsation measuring points are respectively arranged in the runner outlet tube parts, measuring point 1 is in point A (in front of the guide vane) 277mm from the export of tail pipe and point B 215mm (after the guide vane) and point C 139mm (after the runner), the horizontal positions of two points are X and -X, the pressure pulsation measurement points are shown in figure 3.

Three measuring points are set at the outlet of the draft tube, and the positions of the measuring points are shown in figure 3:

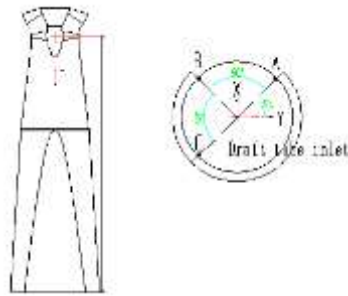
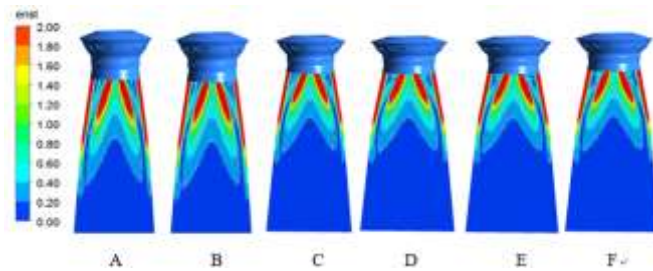


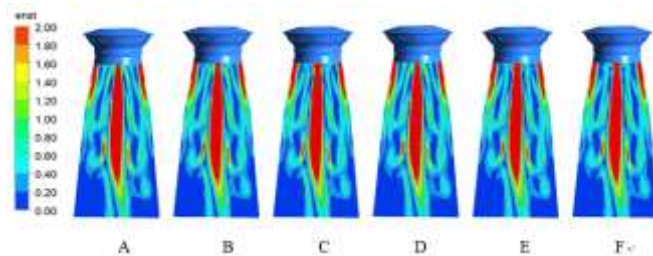
Figure. 3 Pressure pulsation measuring point position

Using the numerical simulation software ANSYS Fluent 18, the wake of the tubular turbine under different on-cam operating conditions is calculated and analyzed, and the vortex diagram, enstrophy and pressure fluctuation time domain diagram of the draft tube are obtained.

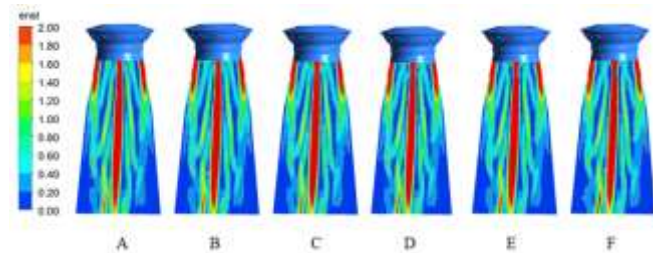
The results are shown in Figure 4 and 5.



(1) blade is 13°, guide vane is 39°



(2) blade is 13°- guide vane is 43°



(3)blade is 13°- guide vane is 47°

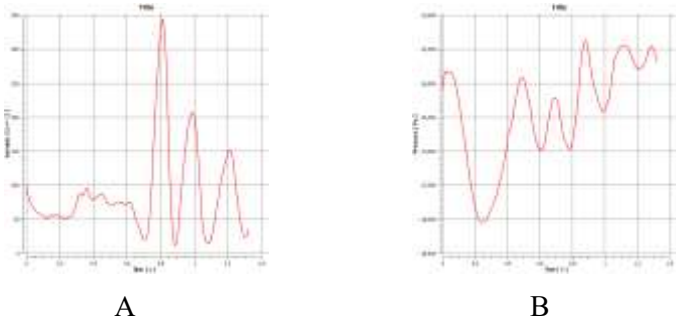
A-45° B-135° C-225°D-315°E-405° F-495°

Figure. 4 Fixed blade 13°different opening of the guide vane vortex vector of the draft tube

As can be seen from Figure 4, when the Straflo turbine draft tube is in the condition of fixed pitch 13°, the distribution of different guide vane opening under the vortex blade is shown. When the blade is 13° and the guide vane is 39°, the wall of tail pipe and the circumferential passage of tail pipe have short vortex, and the side wall of the vortex is relatively longer than the circumferential vortex flow, the vortex flow extends from the entrance of the tail pipe to the 1/3 of the entrance; when the blade is 13° and guide vane is 43°, the center of the side wall and tail water channel have shown the vortex, the vortex flow is short, the vortex flow extends from the entrance of the tail to the 2/3 of the entrance. Under the condition of 13° of blade and 47° of guide vane, the vortex in the tail water channel center further extends, from the entrance of the draft tube extends to the tail water outlet, occupying the entire tail pipe flow center, with no change in the side wall vortex.

It can be seen from the change of different guide vane vortex in the figure that, in the condition that opening is smaller, namely it is away from the on-cam operating condition, vortex occurs mainly in the tail pipe wall and circumferential passage of tail pipe, at this time the vortex is short, the occupied space is small, therefore the dissipative vorticity is small and turbine machine is of low efficiency; with the increase in the guide vane opening, the working condition is near the on-cam operating condition, the circumferential vortex of the tail flow passage turns into a center vortex of the tail water channel with little change in the vortex of the surrounding wall, and in this case the vorticity dissipation increases, energy recovery effect of tail pipe improves, and the efficiency of turbine machine improves; while further increasing opening, this condition is on-cam operating condition, the tail water channel with vortex center becomes longer, the side wall vortex is basically unchanged, and in this case the vorticity dissipation further increases, energy recovery effect of the tail pipe becomes better, and turbine efficiency reaches the optimal interval.

The measuring points are arranged in the area where the enstrophy and pressure fluctuation in the draft tube are obvious, that is, in the middle of the draft tube, and the variation law of the vortex belt and the pressure fluctuation with time can be obtained by measuring points. By comparing the two, the researchers find the relationship between them, enstrophy $\mu_{\text{eff}} |\omega|^2$ can be expressed by Variable 2, unit is s^{-2} , fluctuation with pressure is expressed as pressure, and the unit is pa.



(1) blade is 13 °guide vane is 39 °

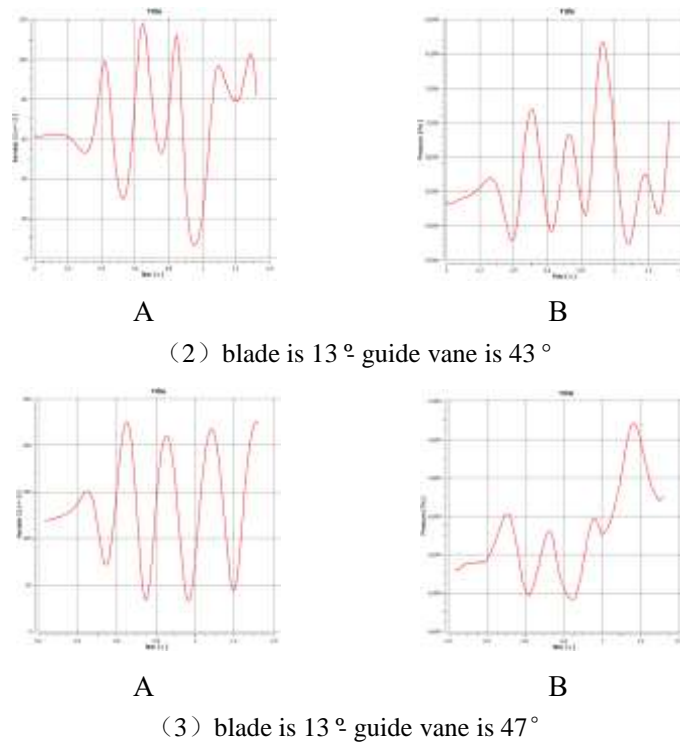


Figure. 5 Fixed blade 13 °different opening of the guide vane parameter change of the draft tube

Figure 5 is the time domain parameter change for a fixed pitch 13° under small opening, in which figure A refers to the change of vortex in time domain, figure B is the power spectrum of the corresponding pressure fast Fourier. It can be seen by the comparison of figure A and B that, at the same time when the enstrophy is in the wave crest, the pressure fluctuation is in the trough, on the contrary, when the enstrophy is in the trough, the pressure fluctuation is in the wave crest. The trend of the enstrophy and that of pressure fluctuation just show the opposite trend, so it can be judged that there are some correspondence with the enstrophy and the pressure pulsation, the peak value change of the enstrophy and pressure fluctuation shows the opposite relationship.

There is a correlation between the enstrophy and pressure fluctuation from the above analysis, and this correlation makes the enstrophy have a certain influence on the pressure pulsation, the vortex induces a low frequency ripple. When enstrophy increases, pressure pulsation frequency reduces. Therefore, it can be concluded that under on-cam operating condition, the larger the enstrophy, the greater the energy dissipation of the draft tube and the better energy absorption of the draft tube, so the efficiency of the runner is higher.

4. Conclusion

In this thesis, the numerical simulation method is used to analyze the flow characteristics in the draft tube. Through the analysis of the calculation results, we can draw the following conclusions: Under non on-cam operating condition, tail pipe wall and circumferential passage of tail pipe form short vortex, the smaller vorticity dissipation, the smaller enstrophy, the larger pressure pulsation frequency, the lower the turbine efficiency. The vortex induces the low-frequency pressure pulsation, the larger enstrophy, the lower pressure pulsation frequency,

the larger pressure pulsation, the larger vibration of hydraulic turbine; when it is close to the on-cam operating condition, the vortex of the wall has little change, the circumferential vortex in the basic cone evolves into one or more vortex flows into the center zone, the vorticity dissipation continues to increase, the energy recovery tube becomes better, turbine efficiency has improved, and pressure pulsation is small, the vibration of hydraulic turbine is small.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by National Key R & D Program of China (2018YFB0905200), Open Fund of Key Laboratory of Fluid and Power Machinery (Xihua University), Ministry of Education Sichuan (Grant No. szjj2017-089 and Sichuan Science and Technology Department (No. 17CZ0034), and Xihua University (xjjg2017083).

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