

Flow characteristics on the blade channel vortex in the Francis turbine

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Abstract. Depending on the long-term hydraulic development of Francis turbine, the blade channel vortex phenomenon was investigated systematically from hydraulic design, experimental and numerical computation in this paper. The blade channel vortex difference between the high water head and low water head turbine was also analyzed. Meanwhile, the relationship between the blade channel vortex and the operating stability of hydraulic turbine was also investigated. The results show that the phenomenon of blade channel vortex is an intrinsic property for Francis turbine under small flow rate condition, the turning-point of the blade channel vortex inception curve appears at low unit speed region, and the variation trend of the blade channel vortex inception curve is closely related to the blade inlet edge profile. In addition to, the vortex of the high water head turbine can generally be excluded from the stable operation region, while which is more different for the one of the low water head turbine.

1. Introduction

The so-called blade channel vortex is a phenomenon of continuous eddy flow between two blades of a Francis turbine runner, in the hydraulic machinery research fields. It's a natural phenomenon of the Francis turbine, which roots in the room between two blades and disappears in the entrance of the draft tube. Some hydraulic turbine units will suffer serious blade channel vortex at the 60% rated output. Nevertheless, it may also appear at the 30% rated output. The blade channel vortex phenomenon, which is an essential observation and experiment indexes, has been applying to preliminary test and acceptance test in model water turbine.

The general opinion is that the blade channel vortex is a great incentive for the operation stability of a turbine, but not necessary factors. The hydraulic action is a very complex natural phenomenon. a signal factor or the combined effect of many factors together, such as the material properties of metals, the geometry of flow passage components, the frequency characteristics of rigid body, and so on, may induce serious noise, pressure fluctuation, cavitation erosion, resonance etc. In some cases, there is may no serious impact on the turbine unit stability operation although some turbines have existed the blade channel vortex.

When the blade channel vortex affect the stable operation of hydraulic turbines, in some hydropower plants, the stable turbine operation scope is delimited to avoid the unsteady operating region, in others, aeration method is used for reducing noise, pressure fluctuation and improving the operating condition[1]. The third scheme is that the modification or replacement measure of the runner

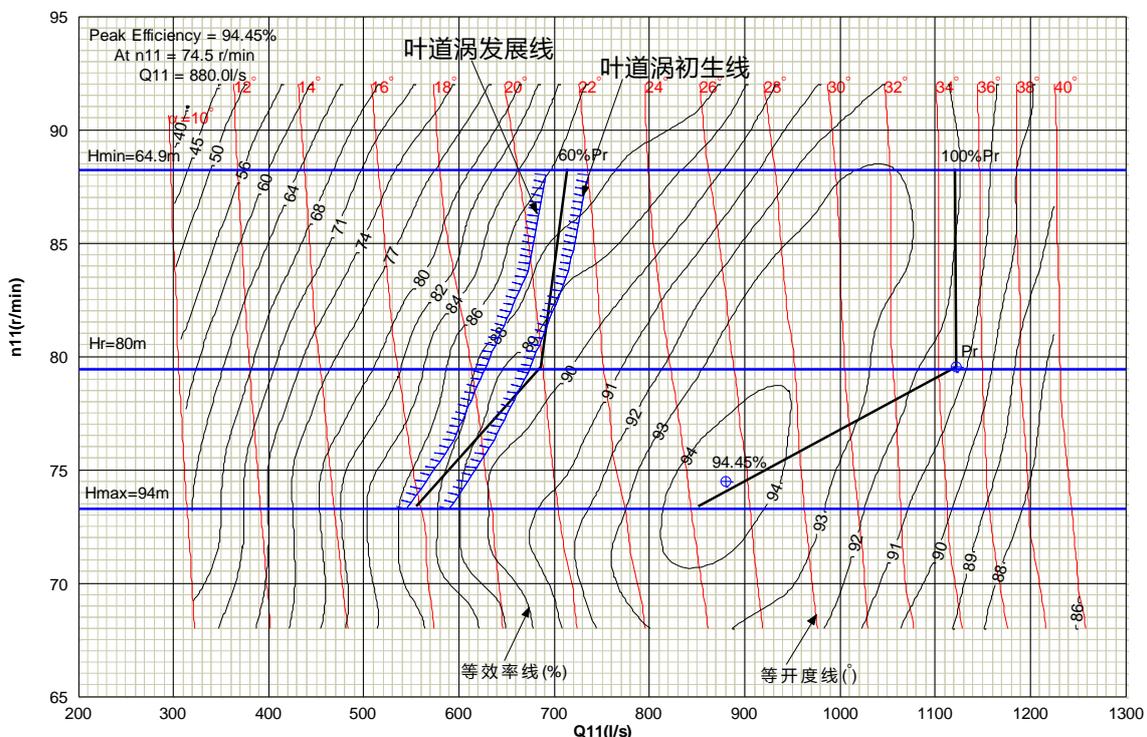


is adopted to achieve stable operation of the hydraulic turbine based on the hydraulic design. Therefore, we must have a correct understanding for the form of the blade channel vortex in order to guide the hydraulic design and engineering practice of hydraulic turbine.

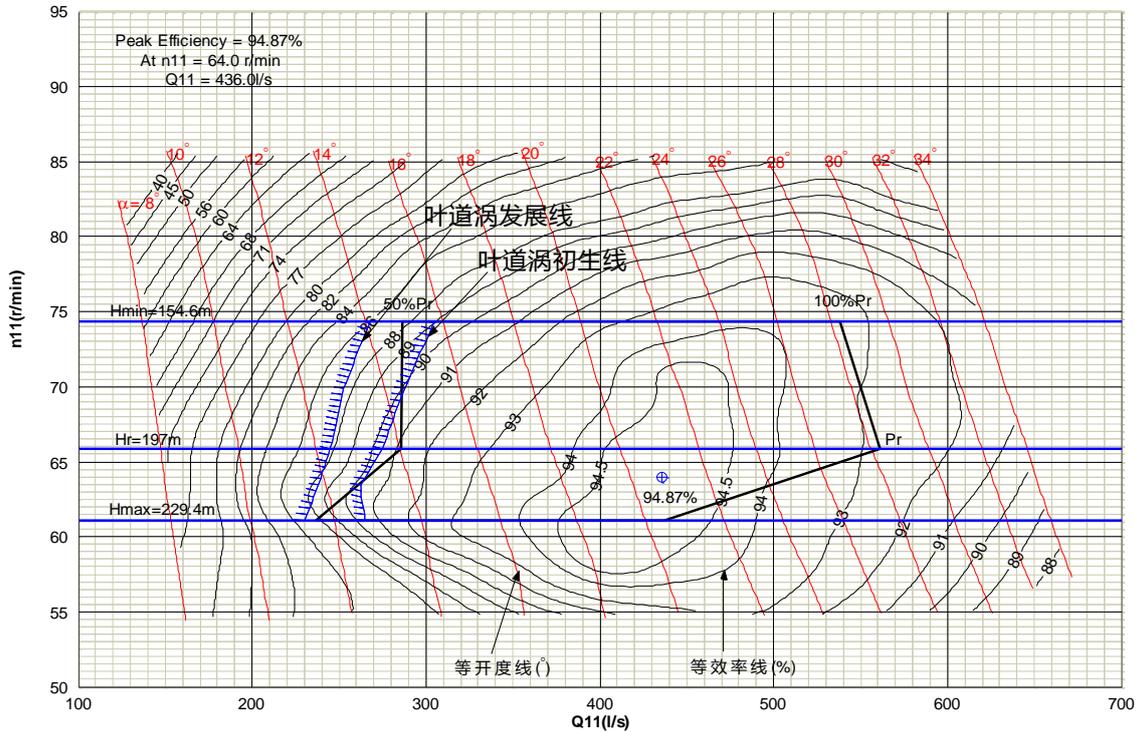
A great lot of related studies have been carried out with a focus on the formation mechanism as well as its influence on the operation characteristic. Xiao Yexiang et al. took a numerical analysis of blade channel vortex in Francis turbine at part load, they investigated the characteristics of the unsteady flow dominant frequencies at different monitored points and concluded the dominant frequencies of blade channel vortex were a low frequency[2]. Zhang Hongming et al. present numerical simulation of blade channel vortex in a low head Francis turbine using OpenFoam code, the simulation results have shown that using cavitation model to analyze blade channel vortex is very effective[3]. A 2D numerical simulations of blade-vortex interaction in a darrieus turbine is given for instance by Amet E. et al.[4], and the results are compared qualitatively with the visualization of the **vortex** shedding of Brochier. The occurrence of the blade channel vortex between the turbine runner blades is discussed depending on the mechanism calculation, and the frequency of vortex cavity is analyzed form Chen jinxia et al.[5]

2. Model test of blade channel vortex phenomenon

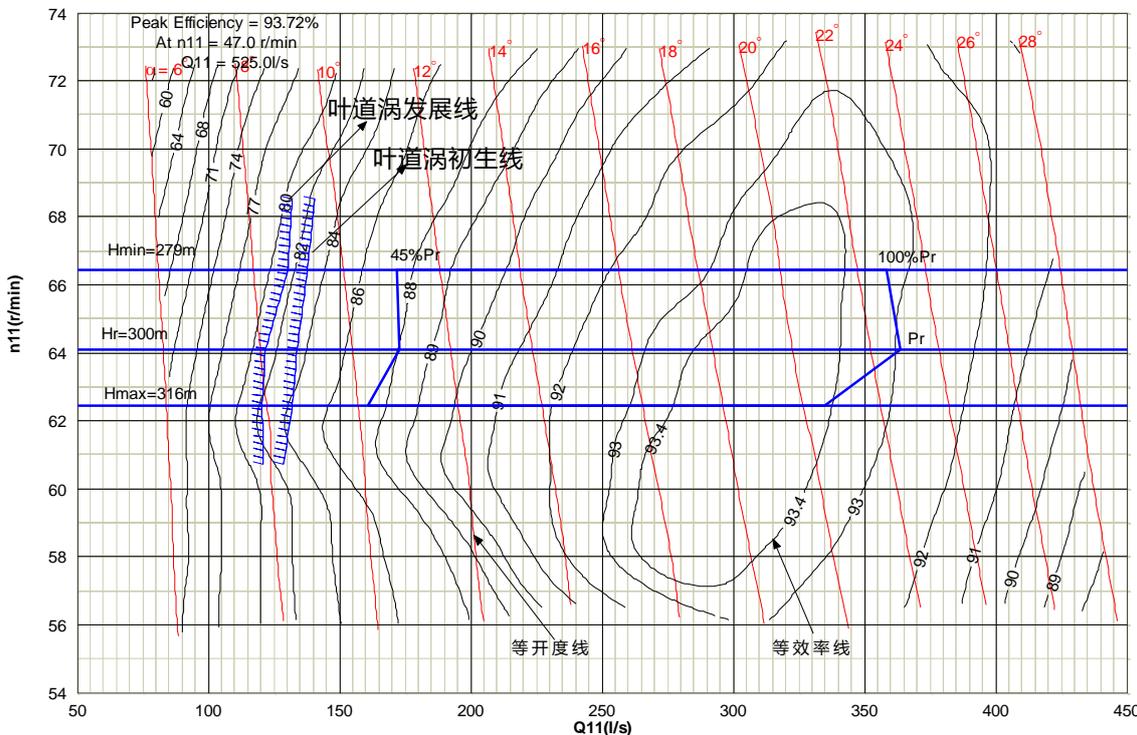
A determinant about the blade channel vortex in the model acceptance test is generally believed that, when the vortex occurs in three blade channels of the runner, defined as the blade channel vortex inception, while it is defined as the development of blade channel vortex if all the blade channel vortex phenomenon takes place. The inception curve and development curve are given to express the blade channel vortex characteristics in the model combined characteristic curve chart of hydraulic turbine. Although the manifestation pattern and the overall development trend of the blade channel vortex are similar for different turbines, the model turbine development aims at different water head range, so its characteristics in different model combined characteristic curve is some different.



(a) 100m water head



(b) 200m water head



(c) 300m water head

Figure 1. Blade channel vortex curves under different water heads

The blade channel vortex of the low water head turbine occurs near optimum area of the model combined characteristic curve while the blade channel vortex of the high water head turbine is away from optimum area, but they both appear in low flow rate area, that is to say, it emerges in low load

condition, below 60% output for the prototype turbine. The representative test curve of the blade channel vortex in different water heads is shown in Figure 1 (a) ~ (c), and from which we can clearly see that similarities and differences of the blade channel vortex in different water heads. The turning-point of the blade channel vortex inception curve appearing at low unit speed region is shown in Figure 1 (b). Almost certainly, the variation trend of the blade channel vortex inception curve is closely related to the blade inlet edge profile.

3. Cause of blade channel vortex formation

About the formation mechanism of the blade channel vortex, some scholars think that blade incidence angle is too large when the guide vane opening is small, form flow separation in the blade leading edge, and result in blade channel vortex generation[6]. Others demonstrate that the flow separation near the crown of runner leading edge gives rise to blade channel vortex generation. All of them agree that flow separation leads to blade channel vortex generation.

A majority of hydraulic plants have adopted the runner with X type blade since emerging of it. As figure 2 shows that one of the hydraulic design characteristics of the X type blade is inlet blade angle increasing gradually from runner crown to band. In order to keep the triangle of inlet velocity basically identical, as showed in Figure 3, the blade inlet edge is also correspondingly increase from the crown to the band.

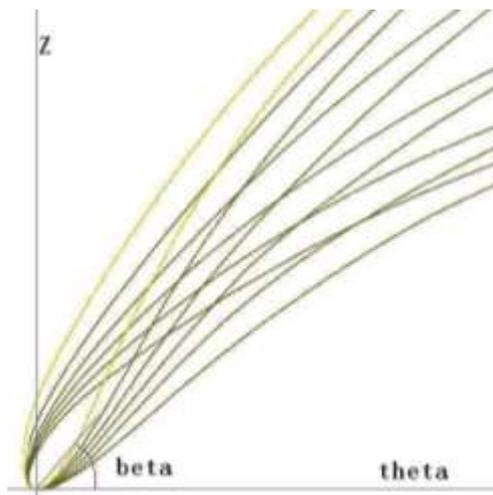


Figure 2. Inlet blade angle beta

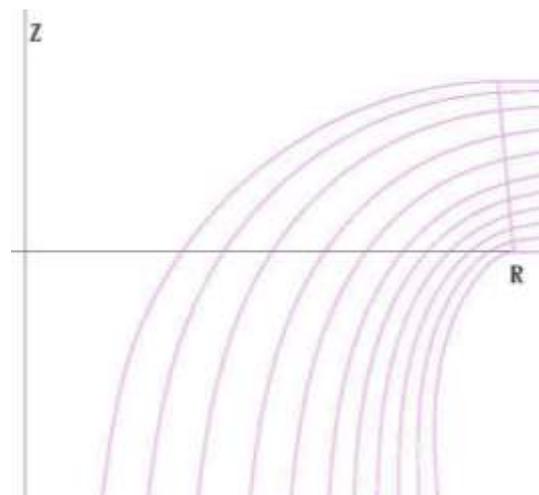


Figure 3. Blade inlet edge in R-Z

According to the results of numerical calculation, for all runners with X type blade, its incidence angle near the band is greater than that near the crown. In theory, if the occurrence of flow separation in the blade suction surface of runner inlet should also be near the band superior to near the crown, however, observation indicates it mostly originates from the runner inlet near the crown position. In addition, theoretically, a large negative incidence angle also leads to flow separation on the blade pressure surface when the guide vane opening is enough large, but experimental results show that eddy flow phenomenon in large flow condition mainly shows the cavitation characteristic, and is defined as cavitation vortex. Cavitation vortex occurs mainly in the low water head and large flow rate condition, as shown in figure 4.

The fundamental reason of blade channel vortex appearing is the turbine operating at the low flow condition with small guide vane opening, and flow separation only incentives channel vortex appearance. Because the blade of Francis runner channel is fixed, the internal flow state of runner will be changed obviously as deviation from the optimum operating condition. Flow velocity increasing result in cavitation occurrence, while a low flow rate lead to blade channel vortex appearing. At the optimum operating condition, steady pressure flow continuously passes through the blade channel of runner, while a marked drop of flow rate, this continuous steady pressure gradient will be broken,

partial radial flow separation under the action of the tangential viscous force spins to form blade channel vortex.

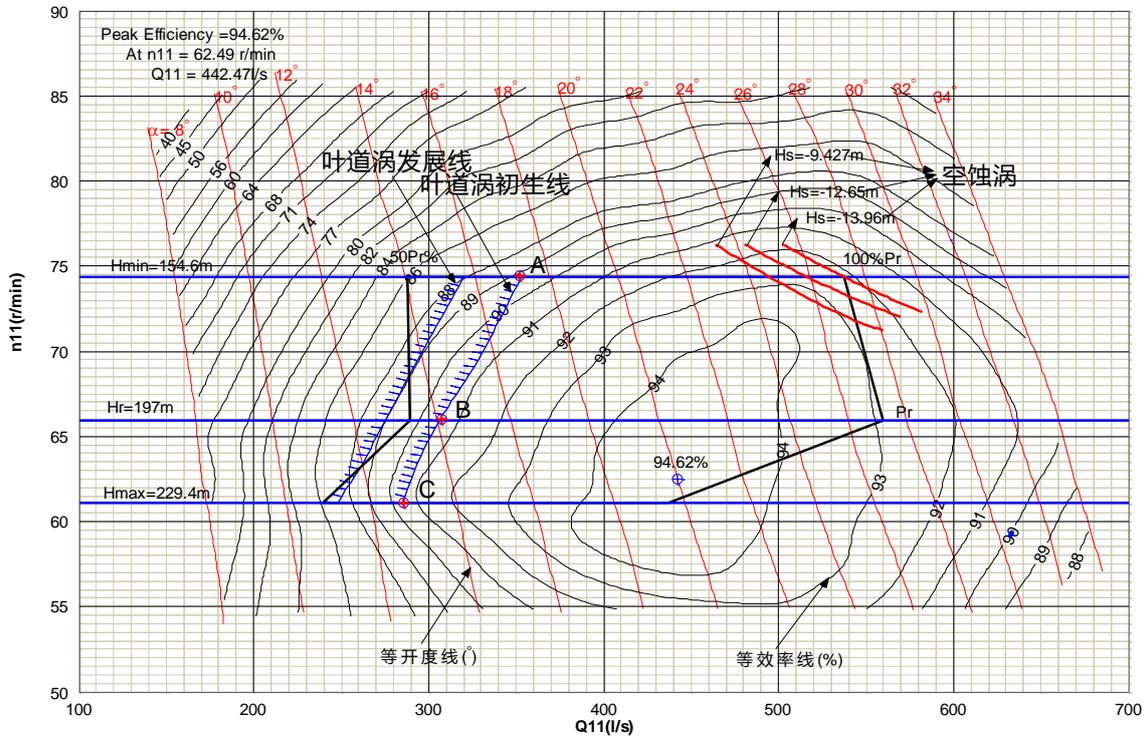


Figure 4. Blade channel vortex and cavitation vortex curve

Characteristic of blade channel vortex can be analyzed by velocity triangle. In figure 4, the curve of variable speed with identical water head marks two operating condition points A and B of the blade channel vortex. Compared with point A, unit speed n_{11} , unit discharge Q_{11} and opening a , decreasing entirely at the point B. As shown in Figure 5 of the velocity triangle, the incidence angle of the point B is larger than that of the point A, and the absolute velocity of the point B is larger than that of the point A. So, two velocity triangles are neither equal nor similar for two operating points A and B.

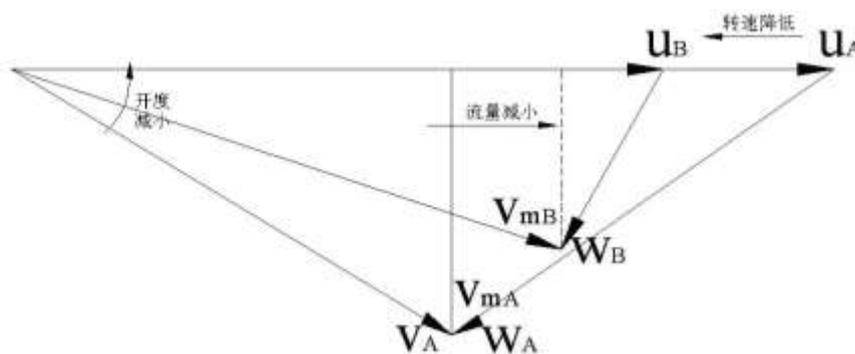


Figure 5. Velocity triangle of blade channel vortex at operating condition A and B

According to test results, the blade channel vortex is expressed by the blade channel vortex inception curve and development curve. No existing absolute symmetric flow in the hydraulic turbine, under the action of the spiral casing and the stay vane relative symmetric flow can occur only in optimum operating condition. For this reason, forming condition of the blade channel vortex is bound to emerge in a circumferential direction under low flow operating condition, and results in blade

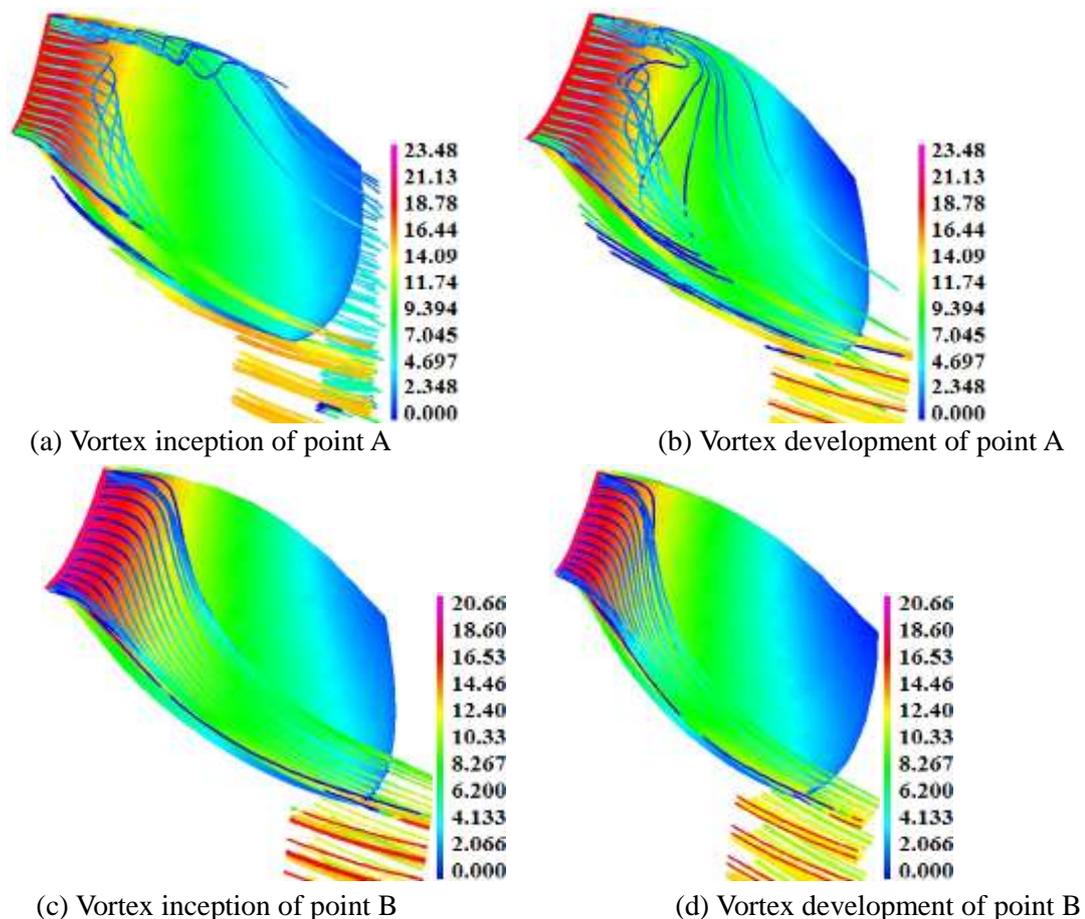
channel vortex inception. With the flow further decrease, all of blade channels of runner will reach blade channel vortex forming condition, which is called as the blade channel vortex development curve.

The author thinks that the blade channel vortex is induced by flow separation only is a superficial phenomenon. When the flow rate drops to a certain extent with an appropriate incidence angle, is the fundamental reason of the blade channel vortex forming.

4. Numerical results of blade channel vortex

Numerical computation was carried out for the three points A, B and C in figure 4, and blade channel vortex appearance and corresponding development was analyzed, as shown in figure 6. Flow pattern of the blade channel vortices and their evolving rule in the three operating condition points is not the same. In the operating condition point A, the blade channel vortex originates in the flow separation of the runner crown, the blade channel vortex of the point C roots in the flow separation of the blade leading edge, while the blade channel vortex flow state of the point B is not belong to the conventional category.

The common features of the different kinds of blade channel vortices are obvious streamline drop appearance in the runner passage. In addition, the blade channel vortex flow state in the development stage is more turbulent and disordered than that in the inception stage.



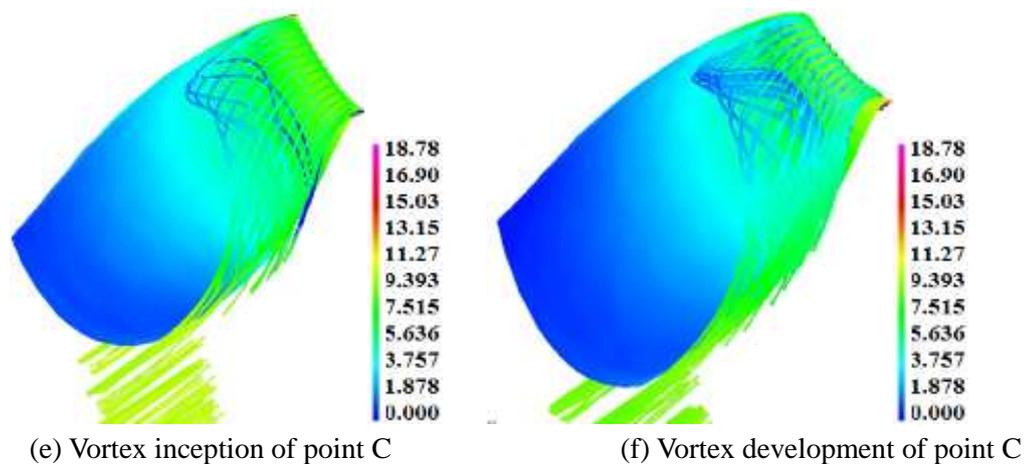


Figure 6. Numerical results of different blade channel vortices

5. Hydraulic design considerations for blade channel vortex

Although the turbine blade channel vortex cannot be eliminated, in a certain water head range the vortex characteristics can be improved in hydraulic design stage, namely it can be shifted in a certain range towards small flow rate direction.

Two different runner schemes for a power station are shown in figure 1(b) and (c) respectively. From the efficiency and blade channel vortex point of view, the scheme in figure 1(b) is superior to that in figure 1(c), Not only its efficiency is higher, but also the blade channel vortex is shifted outside the 50% Pr, yet part of the blade channel vortex development curve in figure 1(c) is within 50% Pr.

Generally, there is a positive incidence angle in the runner inlet at the design condition. Numerical and experimental results showed that the larger positive incidence angle, the earlier appearance of blade channel vortex, on the contrary, the smaller positive incidence angle, the latter emergence. While the magnitude of positive incidence angle will affect the level of optimum efficiency and restrict the offset of the optimum operating condition point. Besides, the evolution of blade channel vortex is impacted by the runner passage profile, the narrower turbine meridional passage contour, the better adaptability of turbine to low flow rate, and the inception curve of blade channel vortex will shift toward the low flow rate condition, and vice versa. Of course, the decreasing of meridional passage sectional area will give rise to the reduction of the optimum efficiency. So the engineers must conditionally select various hydraulic parameters based on the actual situation of hydropower plant in order to realize the excellent comprehensive performance of hydraulic turbine.

6. Effect of blade channel vortex on the turbine unit stability

Generally, the blade channel vortex doesn't cause serious erosion damage to the blade surface as the cavitation. However the pressure fluctuation amplitude of the turbine will significantly increase in small guide vane opening condition. It's a blind subjective judgment that the blade channel vortex inevitably lead to the turbine unit instability, and it's too stringent in a bidding document that Forced to exclude blade channel vortex from the turbine unit stability operation range[7-9]. In fact, for high water head turbine it's uncomplicated to eliminate blade channel vortex under 40% rated output power, while extremely difficult excluding below 60% rated output power for low water head turbine, so it's essential to make a different treatment for the blade channel vortex in different water head range[10].

The test and operation experience indicates that at small guide vane opening condition the blade channel vortex will form in the runner passage, and result in high pressure fluctuation amplitude, but its frequency characteristics generally take the forms of typical draft tube vortex rope frequency. As long as the blade vortex did not induce hydraulic resonance or damage, and turbine unit vibration, noise, fatigue and other indicators is in the stability requirements, it is believed that the blade channel vortex is stable, and the units can operate stably in the condition of small guide vane opening and a

short period.

7. Conclusion

(1) The blade channel vortex is an intrinsic property for Francis turbine under small flow rate condition.

(2) The blade channel vortex is an inevitable response of runner passage inadaptation for the small flow rate, and the blade leading edge stall in small guide vane opening is just one of the causes of inducing blade channel vortex.

(3) Despite identical regulation and trend of the blade channel vortex for high water head and low water head turbine, the vortex of the high water head turbine can generally be excluded from the stable operation region, while the one of the low water head turbine to achieve this target is more difficult.

(4) Different turbine meridional passage contour has inhibited the inception and development of the blade channel vortex in a certain extent, however, cannot be thoroughly eliminated.

Acknowledgement

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