STUDY ON TIP LEAKAGE VORTEX IN AN AXIAL FLOW PUMP BASED ON MODIFIED SHEAR STRESS TRANSPORT *k-ω* TURBULENCE MODEL

by

Desheng ZHANG**, *Dazhi PAN, Weidong SHI, Suqing WU, and Peipei SHAO

Research Center of Fluid Machinery Engineering and Technology,
Jiangsu University, Zhenjiang, China

Short paper
DOI: 10.2298/TSCI1305551Z

The tip leakage vortex structure and trajectory in an axial flow pump were investigated numerically and experimentally based on the modified shear stress transport k-ω turbulence model. Numerical results were compared with the experimental leakage vortex trajectories, and a good agreement was presented. The detailed trajectories of tip leakage vortex show that the starting point of tip leakage vortex occurs near the leading edge at small flow rate, and it moves from leading edge to about 30% chord length at design flow rate. At larger flow rate condition, the starting point of tip leakage vortex shifts to the middle of chord.

Key words: *axial flow pump, tip leakage vortex, trajectory, numerical simulation*

Introduction

The flow field of the rotating machinery is very complex, especially near the wall region. Tip leakage vortex (TLV) in axial flow pump is mainly caused by the leakage flow entraining with the main flow of the blade suction side, which could cause severe effects on pump performance such as the blockage in flow passage [1], efficiency losses [2], noise generation [3], TLV cavitation [4, 5], and rotating stall [6]. The low pressure area of vortex core often induces noise, vibration and cavitation erosion on the end wall of the impeller. The numerical method, such as Reynolds average Navier-Stokes and large eddy simulations, have been important ways to investigate the mechanisms of TLV. Jang *et al*. [7] found that the breakdown of TLV induces high-pressure fluctuations on rotor blades based on LES.

In this paper, in order to investigate the flow structure and TLV trajectory in an axial flow pump at multi-conditions, a new method to identify the trajectory of tip leakage vortex was proposed, namely swirling strength method, and the characteristics of TLV trajectory is revealed numerically and experimentally based on the comparisons and analysis.

Numerical method and pump geometry

Modified shear stress transport k-ω turbulence model

The modified turbulent model in discussion is based on shear stress transport (SST) *k-ω* equations, which is improved by adding random number generation (RNG) *k-ω* as correction terms using analogy. Preliminarily, SST model is established on the basis of transformed

* Corresponding author; e-mail: zds@.ujs.edu.cn

standard k-ε and k-ω model. However, the inaccuracy on separation calculation of standard k-ε leads to the adding term of RNG k-ε in order to have a better prediction. The equation k in the new model is static, only being revised in accordance to the dissipation equation. The dissipation equation of original RNG model is:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_i}\left(\alpha_k\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon \tag{1}$$

Associate with $\omega=\varepsilon/C_\mu k$:

$$\frac{\partial(\rho\omega)}{\partial t}+\nabla(\rho U\omega)=\nabla\left[\left(\mu+\frac{\mu_t}{\sigma_{\omega3}}\right)\nabla\omega\right]+(1-F_1)2\rho\frac{1}{\sigma_{\omega2}}\nabla k\nabla\omega+\alpha_3\frac{\omega}{k}P_k-\beta_3\rho\omega^2-R_\omega \tag{2}$$

where $R_\varepsilon=\{[C_\mu\rho\eta^3(1-\eta/\eta_0)]/(1+\beta\eta^3)\}\omega^2$, $\eta = Sk/\varepsilon$, η_0 = 4.38, β = 0.012, $\mu_t = k/\omega$, and C_μ = 1.

Then the dissipation equation in the modified SST model is obtained which would be applied in the following simulation.

Pump geometry and meshing

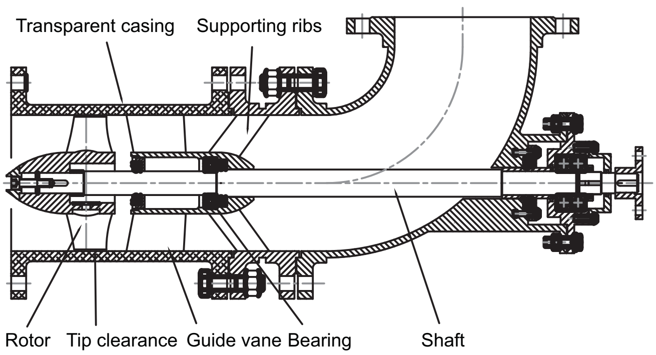

Figure 1. Cross-section of model pump

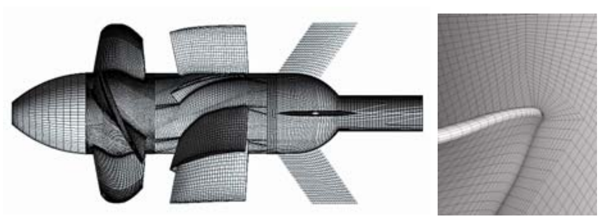

Figure 2. Computational mesh

The axial flow pump model is presented in fig. 1. Its detailed geometrical parameters are: flow rate Q = 392 m^3/h, head H = 3.2 m, rotation speed n = 1450 rpm, impeller diameter D_2 = 200 mm, impeller blade number is 4, guide vane number is 7. The casing of impeller and guide vane is made of transparent plexiglass to observe the TLV cavitation. This paper focuses on the studies of gap flow and TLV and separation flow field within wall boundary layers, thus the gap region require the high density mesh which is shown in fig. 2.

Results and discussion

Tip leakage vortex structure

According to the tip leakage vortex streamlines location, five sections were selected within blade passage which are close to impeller casing end wall, namely A, B, C, D, and E as shown in fig. 3(a). The streamlines of tip leakage flow in axial flow pump with tip clearance 1.0 mm, the iso-surface of tip leakage vortex with swirling strength ISO surface (900 s^{-1}) and swirling strength at five cross-sections were analyzed together. It is obvious that the tip leakage vortex is formed due to the pressure difference between blade pressure side (PS) and suction side (SS), and the relative motion between blade rim and impeller casing. Figure 3(b) shows that high-speed jet flow occurs in the tip gap which rolls up with mainstream within blade passage due to the high-speed rotation of impeller. The entraining direction of tip leakage vortex is opposite to rotating direction. As shown in fig. 3(b), the velocity of tip leakage flow reaches the maximum value at 10% chord length, which is up to about 15 m/s, and the tip leakage flow velocity is decreasing gradually from leading edge to trailing edge. As the pressure of blade suction surface increases gradually toward the trailing edge, the pressure difference decreases gradually, resulting in the decrease of the leakage vortex swirling strength. At about 10% chord length, the starting point of tip leakage vortex occurs, and the vortex swirling strength is higher in this position. Vortex swirling strength dissipates gradually as the tip vortex moves backward, and the diameter of core and the extent of passage are affected by the vortex movement and development. As shown in fig. 3(c), five sections all have the regions of maximum local swirling strength. It is obvious that the streamlines of TLV pass through cylindrical region with maximum swirling strength of five sections in fig. 3(c). The swirling strength ISO surface (900 s^{-1}) in fig. 3(d) indicates that tip leakage vortex trajectory coincides with the streamlines of TLV, so the trajectory of TLV can be described through swirling strength ISO surface accurately. The region with maximum swirling strength in the section is around the core of TLV in axial flow pump.

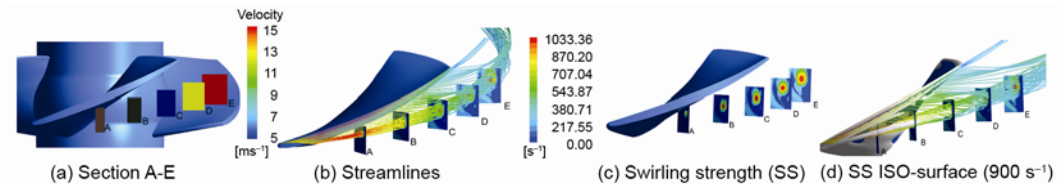

Figure 3. Tip leakage vortex structure *(for color image see journal web site)*

Tip leakage vortex trajectory

The swirling strength in different sections was measured to identify the maximum point as the center of the TLV core, and then maximum value points were connected. So the curve is approximately regarded as the TLV core trajectory. As shown in fig. 4, numerical results show a good agreement with the high speed imaging results. It is proved that the swirling strength method could capture the TLV trajectory correctly, and the modified SST k-ω turbulence model is better for the TLV simulation. The starting point of TLV occurs near the leading edge at small flow rate (Q/Q_{opt} = 0.8). However, it moves to about 30% chord length at design flow rate (Q/Q_{opt} = 1.0). At the larger flow rate condition (Q/Q_{opt} = 1.2), the starting point of TLV shifts to the middle of chord. The main reason is that the maximum pressure difference shifts at different operating conditions, and the starting point of tip leakage vortex moves accordingly. So it is proved that the operating condition of the axial flow pump has a large impact on the trajectory characteristics of tip leakage vortex.

Conclusions

Tip leakage vortex in an axial flow pump was simulated by the modified SST k-ω turbulence model successfully. Numerical and experimental results show that operating condition of axial-flow pump has a great effect on tip leakage vortex trajectory. The trajectories of

TLV show that the starting point of TLV occurs near the leading edge at small flow rate, and it moves from trailing edge to about 30% chord length at design flow rate. However, the starting point of TLV shifts to the middle of chord length at larger flow rate condition.

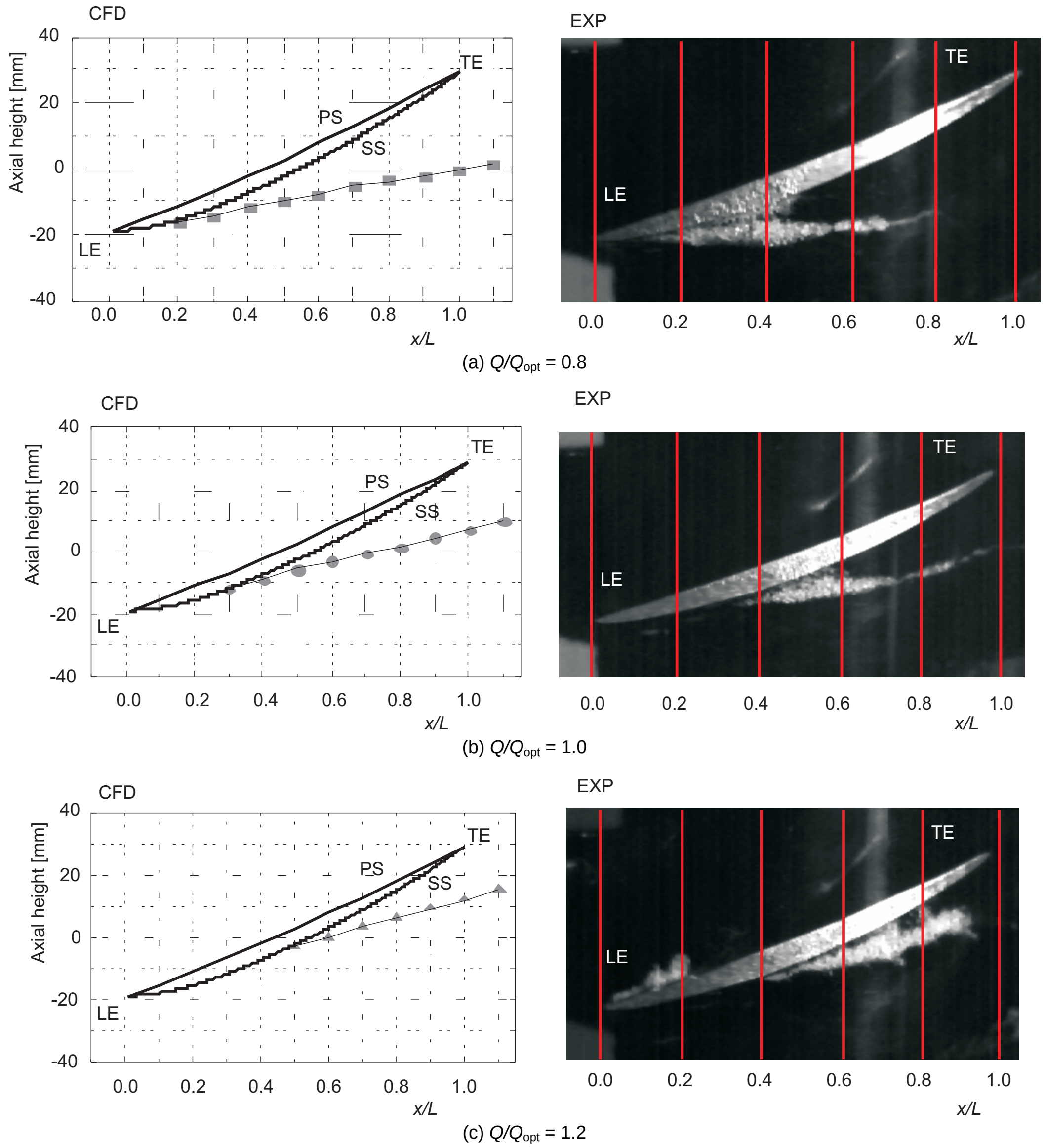

Figure 4. Comparisons of simulation results and experimental results of TLV trajectory (■, ●, ▲)

Acknowledgment

This work was supported by the NNSF of China (No. 51109093, 51079063), Natural Science Foundation of Jiangsu (BK2011503), Postdoctoral Science foundation of China (2011M500117, 2012T50468), Jiangsu Achievements Transformation Project (BA2011126) and PAPD.

References

[1] Chen, G, T., *et al*., Similarity Analysis of Compressor Tip Clearance Flow Structure, *Journal of Turbomachinery*, *113* (1991), 2, pp. 260-271
[2] Li, Y. S., Cumpsty, N. A., Mixing in Axial Flow Compressors: Part I – Test Facilities and Measurements in a Four-Stage Compressor, *Journal of Turbomachinery*, *113* (1991), 2, pp. 161-165
[3] Mailach, R., Lehmann, *et al*., Rotating Instabilities in an Axial Compressor Originating from the Fluctuating Blade Tip Vortex, *Journal of Turbomachchinery*, *123* (2000), 3, pp. 453-460
[4] Farrell, K. J., Billet, M. L., A Correlation of Leakage Vortex Cavitation in Axial-Flow Pumps, *Journal of Fluids Engineering*, *116* (1994), 3, pp. 551-557
[5] Shen, Y. T., *et al*., Tip Vortex Cavitation Inception Scaling for High Reynolds Number Applications, *Journal of Fluids Engineering*, *131* (2009), 7, pp. 071301
[6] Tan, C. S., *et al*., Spike-Type Compressor Stall Inception, Detection, and Control, *Annual Review of Fluid Mechanics*, *42* (2010), pp. 275-300
[7] Jang, C. M., *et al*., Analysis of Vertical Flow Field in a Propeller Fan by LDV Measurements and LES – Part I: Three-Dimensional Vortical Flow Structures. *Journal of Fluids Engineering*, *123* (2001), 4, pp. 748-754

Paper submitted: January 18, 2013
Paper revised: April 26, 2013
Paper accepted: April 27, 2013