PREDICTION OF “S” CHARACTERISTICS OF A PUMP-TURBINE WITH SMALL OPENING BASED ON V2F MODEL

JINTAO LIU

*Department of chemical and biological engineering, Zhejiang University,
 Hangzhou, China
 liujintao86@hotmail.com*

SHUHONG LIU, YULIN WU, YUEKUN SUN AND ZHIGANG ZUO

*State Key Laboratory of Hydrosience and Engineering, Tsinghua University
 Beijing, China
 liushuhong@mail.tsinghua.edu.cn*

The characteristic of a pump-turbine during the whole starting or stopping period couldn't be calculated accurately by CFD method and most of turbulence models were found inaccurate in the calculation of small opening condition, so a proper turbulence model was needed for the further study of pump-turbine. V2F model which was valid to the solid wall and SST $k-\omega$ model were used to calculate the pump-turbine with two openings that one was a small opening and the other was large opening. Results showed that V2F model can be used to simulate characteristics of pump-turbine in the whole opening range and the SST $k-\omega$ model can be used only for large openings. Results of V2F model are accuracy and it realizes the real flow in the near wall region. Results of V2F model can obtain small vortexes and some complex flow phenomenon and they are much different from results of SST $k-\omega$ model. The V2F model might be used to simulate the starting or stopping period of a pump-turbine.

Keywords: Pump turbine; S characteristic; V2F turbulence model; small opening.

1. Introduction

A pump-turbine runs at no-load condition and it is easy to run into the unstable S region during the starting period at turbine mode, even lead to failure synchronization¹. In order to understand the mechanism of instability of a pump-turbine during the start-up by numerical simulation, the method to calculate S characteristics with small openings should be carried out.

At present, numerical simulations of turbine mode was widely used, but few reports could be found on the prediction of braking mode and reverse pump mode, especially no report on the small opening of guide vanes. During the start-up of a pump-turbine at turbine mode, the opening of guide vanes increases from the closed position. The 3 dog-leg low of openings is widely used in many pumped storage power stations. The pump-turbine runs with a small opening for a long time about 20 minutes during the starting period². The gap between two adjacent guide vanes is small that the grid refinements are

difficult to define. In addition, the fluid passes through the gap at a high speed, it increases the y^+ of vane boundaries³ and it will cause errors during the calculation by RANS model and standard wall function. Therefore, a suitable turbulence model is needed in this small opening condition.

In recent studies, Liu^{4,5} and Zhang⁶ applied RANS model and standard wall function to simulate the S region, but they all focused on big openings. With small openings, the flow was complex and the standard wall function couldn't simulate the real flow near the wall, so the V2F model which does not need to make use of wall functions was chosen for the calculation. Few reports can be found on the numerical simulation of turbomachineries based on V2F model^{7,8}.

2. Geometry and Grid

2.1. Main difference

As experimental data is tested by a model, the numerical computation is also carried out using the structure of model. The parameter of pump-turbine is showed in Table 1. D_1 denotes the runner outlet diameter in turbine mode; B denotes the number of blades; n denotes the rotational speed of the runner; N_s denotes the specific speed of the pump-turbine; γ_o is the whole opening of guide vanes.

Pump-turbine's structure is shown in Figure 1. The model's grids which are unstructured hexahedron and tetrahedron are carried out by ICEM shown in Table 2. In order to make y^+ as small as possible, there were 10 layers of grids in boundary layer. The mesh grids of the impeller are shown in Figure 2.

Table 1. Parameter of pump-turbine.

D_1/m	B	n/rpm	$\gamma_o/^\circ$	N_s
0.24	9	900	34	112

Table 2. Mesh number of each sub-domain.

Mesh types	Tetrahedron	Hexahedron		total
regions	Case and vanes	Impeller	Draft tube	
Mesh numbers	2361198	2144730	600480	5106048
Node numbers	1339316	2203028	622402	4164746

Fig. 1. Model of Pump-turbine.

Fig. 2. Structure of boundary layer.

3. Numerical Model

The V2F model which is similar to the Standard $k-\varepsilon$ model incorporates some near-wall turbulence anisotropy as well as non-local pressure-strain effects. It does not need to make use of wall functions because it is valid up to solid walls¹⁰. Turbulent quantities are obtained from two more equations which are the transport equation (1) and the relaxation function (2) in addition to standard k and ε .

$$\frac{\partial \overline{v^2}}{\partial t} + U_j \frac{\partial \overline{v^2}}{\partial x_j} = kf - \frac{\overline{v^2}}{k} \varepsilon + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma} \right) \frac{\partial \overline{v^2}}{\partial x_j} \right], \quad (1)$$

$$L^2 \nabla^2 f - f = \frac{C_1 - 1}{T} \left(\frac{\overline{v^2}}{k} - \frac{2}{3} \right) - C_2 \frac{P_k}{\varepsilon}, \quad (2)$$

where the turbulent viscosity $\mu_t = C_\mu \overline{v^2} T$, L is the turbulence length scale, T is the turbulence time scale, the coefficients are defined as $C_\mu=0.22$, $\sigma=1$, $C_1=1.4$, $C_2=0.45$

Velocity of the inlet and pressure of the outlet were set during the calculation. The Multiple Reference Frame model was applied for the impeller. SIMPLEC algorithm was used as a relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field. Models with different grid sizes were used to verify the validity of the calculation. Number of cells varies from 2 million to 7.5 million with the ratio of grid growth of 1.3. Results show that only 3% of variation in head can be seen when the total cell number was more than 3.5 million. All results were simulated based on steady calculation.

4. Results

4.1. S characteristics with different openings

Fig. 3 shows calculation results of S characteristics based on the V2F model and SST $k-\omega$ model. Two kinds of opening of guide vanes are calculated that one is a big opening which is about 70% of whole opening and the other one is a small opening which is 17% of whole opening. When the opening of guide vanes is large enough, modest variations of

V2F model and SST $k-\omega$ model can be seen from the comparison with experimental results. Both V2F model and SST $k-\omega$ model and standard wall function can be used to predict the S characteristic of a pump-turbine with large opening degrees. If the opening of guide vanes decreases to a small degree, large differences can be seen between results of V2F and SST $k-\omega$ model. Compared with the experimental result, the calculation result of V2F model is accuracy while the SST $k-\omega$ model isn't suitable for the calculation for small openings.

The relationship between the head and flow rate of the pump-turbine when $\gamma = 6^\circ$ is shown in Fig. 4. In the S region, the head of SST $k-\omega$ model varies greatly from the result of V2F model and the experimental data. Large errors of the torque of the impeller can be seen from Fig. 5 when $Q < 0$. Results of head and torque calculated by V2F model are in good agreement with experimental results.

Fig. 3. S characteristics of different openings.

Fig. 4. H-Q curve when $\gamma = 6^\circ$.

Fig. 5. M-Q curve when $\gamma = 6^\circ$.

4.2. Flow field analysis

In order to analyze why results of S characteristic with small opening have so large difference, three points which are the zero moment point (ZMP), zero flow rate point (ZFR) and a large flow rate point in reverse pump mode (LFRP) in a small opening are investigated showed in Fig. 6.

At ZMP, the result of V2f model has some vortexes in the region between the guide vanes and stay vanes, while the SST model and standard wall function couldn't obtain this result within same mesh grid. When the flow rate is 0, the flow circulates around four stay vanes and the vortex in the gap between two adjacent guide vanes can be obtained. While the result of RANS model and standard wall function doesn't has this phenomenon. When the pump-turbine runs at reverse pump mode at a large flow rate, for small opening, the incidence angle between the flow and inlet of guide vanes is very large, every gap between two adjacent guide vanes has a vortex. But the SST model and standard wall function couldn't obtain the vortexes within same mesh grid.

(a1) ZMP of V2F model

(a2) ZMP of SST k- ω model

(b1) ZMP of V2F model

(b2) ZMP of SST k- ω model

Fig. 6. Velocity vector of three analysis points.

4.3. Velocity distribution near the wall

In order to analyze why the SST varies greatly from the result of V2F model, a line shown in Fig. 7 which is vertical to the vane boundary was chosen and the velocity distribution on this line was analyzed. In Fig. 8, d is the distance to the wall, it can be seen that the velocity distribution of V2F model is quite similar to Prandtl hypothesis near the wall, while the SST model isn't accuracy. This might cause the difference in the calculation result of S characteristic.

Fig. 7. Position of vertical line.

Fig. 8. Velocity distribution near the wall.

5. Conclusions

The V2f could be used in the calculation of S characteristics in the whole range of opening for it can get good result in small opening condition. The V2F model is accuracy in the near wall region. It realized the real flow in the near wall region. V2F is thought to be more accuracy for the prediction of flow field with small opening. The simulation method based on V2F model could be used in the calculation of the starting or stopping period due to the pump-turbine must run in a small opening.

References

1. Z. Mei, *Generation technology of pumped storage power*, Beijing: Machinery Industry Press, 2000.
2. T. Staubli, F. Senn and M. Sallaberger, *Instability of Pump-Turbines During Start-up in the Turbine Mode*, in Hydro, (2008) p.96.
3. FLUENT® Inc., 2005, Lebanon, NH
4. J. T. Liu and L. Q. Wang, *J. Eng. Therm.* **31**, 133 (2010).
5. L. Q. Wang and J. T. Liu, *J. Dra. Irr. Mach. Eng.* **1**, 1 (2011).
6. L. J. Zhang and Z. W. Wang, *Trans. Chinese Soc. Agr. Mach.* **42**, 39 (2011).
7. P. A. Durbin, *Theo. Comput. Fluid Dyn.* **3**, 1 (1991).
8. Y. W. Liu, *J. Eng. Therm.* **29**, 400 (2008).
9. A. Cervone, *J. Fluids Eng.* **128**, 326 (2006).
10. M. Popovac, and K. Hanjalic, *Flow Turb. Comb.* **78**, 177 (2007).