Interaction effects on the unstable discharge-energy characteristic of pump-turbine in pump mode

R Tao\(^1\), R F Xiao\(^1\), W Yang\(^1\), W C Liu\(^2\)

\(^1\)College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
\(^2\)Dongfang Electric Machinery Co., LTD, Deyang, Sichuan Province 618000, China

E-mail: xrf@cau.edu.cn

Abstract. For a pump-turbine, unstable discharge-energy characteristic is an important factor for operating stability. In this study, the rotor-stator interaction effects on the pump-turbine which has the unstable discharge-energy characteristic has been studied. A series of transient CFD simulations under different discharge conditions have been conducted. Through the contrast between the simulations and experiments, it is found out that the energy decline is strongly affected by the flow loss in the adjustable vane. More importantly, the magnitude and direction of fluid flowing into the adjustable vane are varying with the impeller rotating. Disordered flow structure occurs in the adjustable vane and causes the energy losses due to the interaction effects. Based on this study, improvements on the flow uniformity at impeller outlet will help us to solve the unstable discharge-energy problem.

1. Introduction

Reversible pump-turbine is a key component in the pumped storage technology. It always works in complex and variant conditions with high requirement in the operating stability. The unstable discharge-energy characteristic is an important stability issue of a reversible pump-turbine while it works in pump mode. The unstable variation of energy may cause multi-intersections of performance curve and device curve and make the pump-turbine unit working under insecure conditions. Therefore, the pump-turbine unit should avoid operating under unstable discharge-energy range. Moreover, the mechanism of unstable discharge-energy characteristic is necessary to study in depth. Researchers\(^{[1,2]}\) had investigated the unstable discharge-energy characteristic by both computational fluid dynamics (CFD) and experiment. Results show that the unstable discharge-energy characteristic is related to the complex separated flow in the passages. The energy (pump head) declines because of secondary flow, back flow and vortex structure in the flow field. As a reason of operating instability, rotor-stator interactions in turbines or reversible pump-turbines were also studied by researchers\(^{[3,4]}\). Under low discharge conditions, energy loses due to the turbulent flow caused by interaction effects. So, the study on rotor-stator interaction in pump-turbine under unstable discharge-energy conditions is necessary. In consideration of the strongly transient flow under unstable discharge-energy conditions, the Detached Eddy Simulation (DES) turbulence method was used in this study to calculate the flow field of the whole pump-turbine domain. Discharge was altered with keeping a constant vane opening angle of 20 degrees to simulate the flow field under unstable discharge-energy conditions. The rotor-stator
interaction with alternate stall and asymmetrical flow especially under low discharge conditions was analyzed to reveal the mechanism of the generation of unstable discharge-energy characteristic.

2. Models and methods of simulation

2.1. Model of pump-turbine
In this study, the model for investigation was the whole pump-turbine passage which consisted of draft tube (suction chamber), impeller, adjustable vane, stay vane and volute. The geometrical model and its corresponding parameters are shown in figure 1 and table 1.

![Figure 1. The geometrical model of the pump-turbine passage.](image)

**Table 1. Parameters of the pump-turbine model.**

| Parameters                        | Value   |
|----------------------------------|---------|
| Impeller Blade Number            | 9       |
| Diameter at Impeller Blade Inlet (Shroud) | 300 mm |
| Diameter at Impeller Blade Outlet| 514 mm  |
| Adjustable Vane Blade Number     | 20      |
| Stay Vane Blade Number           | 20      |
| Vane Height                      | 57.2 mm |

2.2. Simulation configuration
The flow domain based on the model shown in figure 1 had discretized by using the commercial software ICEM CFD with tetrahedral mesh on the volute and hexahedral on other parts. All the CFD processes were conducted in the commercial software ANSYS CFX. In the turbulence flow simulation, the shear stress transport (SST) turbulence model by Menter [6] was used in the pre-calculation for an initial steady flow field. Then, DES model based on SST equations (SST-DES) was used to calculate the transient flow field by inputting the steady results. The SST-DES model is a favourable method to balance the computer performance with the simulation accuracy [7]. The hybrid formula is used with RANS applied inside attached and mildly separated boundary layers and LES is activated in massively separated regions.

Mesh independent study was conducted in the pre-processes to guarantee the near wall region $y^+$ within the range of 30–300 to make the simulation accurate enough. The mesh type and number of nodes of all the components is shown in table 2. The maximum available opening angle of adjustable vane, $\alpha$ is 32 degrees. In this simulation, the actual opening angle of adjustable vane was set to 20 degrees which is equal to 0.625 $\alpha$. Discharge varied within 8 different conditions with the mass flow rate of 225, 259, 288, 311, 340, 421, 496, 557 kg/s and set as the inlet boundary condition. Other configurations including boundary conditions are shown in table 3.

**Table 2.** Mesh type and number of nodes of all the pump-turbine components.

| Parameters   | Type     | Number of nodes |
|--------------|----------|-----------------|
| Draft Tube   | Hexahedral | 371856          |
| Impeller     | Hexahedral | 115257          |
| Adjustable Vane | Hexahedral | 427180    |
| Stay Vane    | Hexahedral | 542520          |
| Volute       | Tetrahedral | 369533         |

**Table 3.** CFD Simulation configurations.

| Parameters                        | Value   |
|----------------------------------|---------|
| Reference Pressure               | 1 atm   |
| Impeller Rotation Speed          | 1200 rpm|
| Flow Rate at Inlet Boundary      | 225–557 kg/s |
| Pressure at Outlet Boundary      | 0 Pa    |
| Boundary of the Walls            | No Slip Wall |
| Total Transient Periods          | 3 Rotations |
| Time-Steps per Period            | 180     |
3. Flow analysis

3.1. Discharge-energy relationship

The discharge-energy curve with both CFD and experiment values under the condition of 0.625 $\alpha$ adjustable vane opening angle is shown in figure 2 with the discharge coefficient $\phi$ and energy coefficient $\psi$ defined as follow:

$$\phi = \frac{Q_m}{n \omega \rho R_2^3}$$

$$\psi = \frac{2 g H}{\alpha^2 R_2^3}$$

where $\rho$ denotes the density of water, $\omega$ is the rotational speed of impeller, $R_2$ is the radius at the outlet of impeller blade, $Q_m$ denotes the mass flow rate, $g$ denotes the acceleration of gravity (9.8 m/s$^2$), $H$ denotes the head in pump mode. The discharge and energy values were acquired at the last time step of the transient simulation.

As shown in figure 2, the values calculated by CFD tools are similar to the data acquired in experiment with the same variation tendency. The average error of energy between CFD and experiment is less than 4.15% so that this simulation is credible and available for analysis. With discharge value decreased to about $\phi=0.046$, energy increased to a local maximum value and turned to decline. The local minimum value occurred at about $\phi=0.043$ and increased again. With the variation rule above, a hump-like unstable discharge-energy characteristic generated.

3.2. Energy losses in the flow passages

Figure 3 shows the energy losses in the flow passages calculated by CFD. The energy losses in draft tube, adjustable vane, stay vane and volute are stacked on the total energy curve and form the impeller-generated energy. As shown in figure 3, the total loss mainly consists volute loss and stay vane loss. With discharge decreased, the energy losses in the passages increased. Especially, the energy loss in adjustable vane rose rapidly. So, the adjustable vane loss may be the most important factor of the generation of unstable discharge-energy characteristic.

**Figure 2.** The discharge-energy curve under 0.625$\alpha$ adjustable vane opening angle condition.

**Figure 3.** The energy losses in the flow passages.
3.3. Interaction effects on flow uniformity

Considering the rotor-stator interaction, the loss in adjustable vane was derived from the internal turbulent flow which was influenced by the flow uniformity at impeller outlet. Figure 4 shows the meridional velocity and absolute flow angle values at impeller outlet under φ=0.043 and φ=0.063 (BEP) conditions. It is shown that the flow was almost uniform at φ=0.063 (BEP) and asymmetrical at φ=0.043. In the unstable discharge-energy region, meridional velocity $C_m$ performed differences in these 9 impeller passages. The absolute flow angle determined the direction where water went out of impeller and into the adjustable vane.

The schematic vectors and contours of velocity $C$ in the flow passages (near the rotor-stator interface) are shown in Fig 5. From figure 5(a), the impeller outlet absolute velocity at φ=0.043 was asymmetrical with higher value on the suction side and lower value on the pressure side. The magnitude and direction of flow was different in each passage. With impeller rotating, adjustable vane should face a time-varying incoming flow. If an adjustable vane passage aligned with high speed flow region (e.g. the suction side of impeller blade), flow would strike on the leading edge of vane and get through this passage smoothly. Otherwise, the low speed region at impeller outlet (e.g. the pressure side of impeller blade) would cause an unfavourable flow direction which was not along the vane geometry. Water struck the side face of vane, splashed away then formed a local stall and blocked the vane passage. Considering the interactions among all the 20 adjustable vane passages and the influences by stay vane, the internal flow in pump-turbine became more complex.

From figure 5(b), at φ=0.063, the velocity uniformity at impeller outlet made the flow stable and reduced secondary flow in vanes. Therefore, the flow uniformity at rotor-stator interface would affect the unstable discharge-energy characteristic. Weakening the asymmetrical flow field might be helpful to improve the flow uniformity at impeller outlet and reduce the generation of periodic vortex in the vanes. For this reason, study the interaction effects would be useful for pump-turbine to reduce or even eliminates the unstable discharge-energy characteristic.

**Figure 4.** The meridional velocity and absolute flow angle values at impeller outlet.
4. Conclusions

Energy losses in the passages (figure 3) showed that the adjustable vane is the key component which caused the most energy decline. Influenced by the coming flow from impeller, flow field became transient with asymmetrical velocity profile at impeller outlet. Because of the impeller rotating, velocity magnitude and direction changed dynamically. As a consequence, local stall generated alternately and induce the flow losses. On the contrary, a proper coming velocity vector would form a steady flow field in the adjustable vane. In conclusion, the flow uniformity at impeller outlet is the essential factor of unstable discharge-energy characteristic. To study the rotor-stator interaction effects will be conducive to solve the unstable discharge-energy problem.

References

[1] Ran H J, Zhang Y, Luo X W and Xu H Y 2011 Journal of Hydroelectric Engineering 30 175-179

[2] Braun O, Kueny J L and Avellan F 2005 Numerical analysis of flow phenomena related to the unstable energy-discharge characteristic of a pump-turbine in pump mode Proceedings of FEDSM2005 (Houston, TX, USA, June 2005)
[3] Zobeiri A, Kueny J L, Farhat M and Avellan F 2006 Pump-turbine rotor-stator interactions in generating mode: pressure fluctuation in distributor channel 23rd IAHR Symp. on Hydraulic Machinery and Systems (Yokohama, Japan, 17-21 October 2006)

[4] Ruchonnet N, Nicolet C and Avellan F 2006 hydroacoustic modeling of rotor stator interaction in francis pump-turbine IAHR Int. Meeting of WG on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems (Barcelona, Spain, June 2006)

[5] Gagnon J M and Deschenes C 2008 Numerical simulation of a rotor-stator unsteady interaction in a propeller turbine 24th Symp. on Hydraulic Machinery and Systems (Foz Do Iguassu, Brazil, 27-31 October 2008)

[6] Menter F R 1994 AIAA Journal 32 1598-605

[7] Menter F R, Kuntz M 2002 Adaptation of eddy-viscosity turbulence models to unsteady separated flow behind vehicles Proc. Conf. The Aerodynamics of Heavy Vehicles: Trucks, Busses and Trains (Asilomar, CA, USA, 2-6 December 2002)