Experimental research on flow field of high head pump turbine based on PIV test

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Abstract. Pump turbine operating conditions are complex, mainly covering turbine mode and pump mode. Pump turbines have various instability problems during operation, such as S-shaped, pump hump, pressure pulsation and cavitation. PIV (Particle Image Velocimetry) is a very effective test technique for the internal flow field observation of pump turbines. In this paper, the S-shaped, pump hump and pressure pulsation of the pump turbine are tested by PIV technology. The experimental observations show that the internal flow of the pump turbine is extremely complicated. For example, the full quadrant flow characteristics of the S-shaped working condition are observed. It is found that there is a phenomenon of single vortex and double vortex coexisting in the Vane-less area between guide vane and impeller blade of the pump turbine. Through the experimental research in this paper, it can provide useful help for understanding the vortex separation on different quadrant working conditions inside the pump turbine.

1. Introduction

Pumped storage, as the most mature, economical and large-scale energy storage method in the world, has been fully developed in China in recent years. Before 2005, China had built 13 pumped storage power stations with a total installed capacity of 5725MW, accounting for less than 1.3% of the total installed capacity of power generation equipment in this country, with a low level of development. By the end of 2018, the installed capacity of China's pumping and storage power stations has reached 29,990 MW, and the capacity under construction has reached 43,050 MW. The development of pumped storage meets the needs of the safe and stable operation of large power grid and the utilization of new energy.
Pump turbine needs two-way operation, both pump and turbine working mode, operating conditions throughout the pump, pump brake, turbine, turbine brake, reverse pump five operating conditions, the operating conditions are complex and variable. The hydraulic development of pump turbine must meet both the performance requirements of turbine and pump, and the transient transition process characteristics must be considered between different working conditions.

The S shape on in the turbine operating condition and pump hump saddle in the pump operating condition are two important problems for pump turbine safety operation. Pump hump area currently adopt allowance limit operation way, namely, determine the safety margin of the maximum head to hump area not less than 2%, in order to avoid the pump turbine run into the hump zone [1-2]. However, the "S" zone in the turbine operating condition cannot be avoided. No matter it is load increasing in the turbine operating condition or load rejection in the turbine operating condition, the unit inevitably needs to pass through the "S" zone. The "S" characteristic of pump turbine has become the decisive factor affecting the safe and stable operation of pump turbine. In general, the influence of the "S" characteristic of the turbine operating condition on the unit stability in the transition process of the pump turbine is mainly reflected in the following two aspects.

1) The turbine cannot online under the condition of low head

Affected by the characteristics of pump turbine S curve, pumped storage power stations have been built in China. Such as: Tianhuangping pumped storage power station[3] (Hr=526m, Pr=6×300MW), Guangzhou pumped storage power station phase ii (Hr=535m, Pr=4×300MW), Baoquan pumped storage power station (Hr=510m, Pr=4×300MW), Huizhou pumped storage power station [4] (Hr=517.4m, Pr=8×300W), Heimifeng pumped storage power station (Hr=295m, Pr=4×300MW), Xianyou pumped storage power station [5] (Hr=430m,Pr=4×300MW) and other pump turbine units are unable to realize direct grid-connected power generation under low-head condition of the turbine, so they have to be started by non-synchronized guide vane.

2) The unit speed and pressure exceeding the IEC standard value when the turbine is load rejection

A number of power stations have experienced accidents during load rejection. Some have damaged the seals, while others have damaged the generators and hydraulic turbines, flooding the plants and even causing casualties [6]. For example, Huizhou, Xilongchi, Baishan and Japan's Geyegawa have all had such accidents [7-9].

The occurrence of these accidents is closely related to the s-shaped curve of the pump turbine and the core area related to the s-shaped phenomenon is the vane-less region between guide vane and impeller of the pump turbine, whose flow state determines the efficiency, pressure pulsation amplitude, shape of the s-shaped curve or whether there is an s-shaped region. Scholars also study the flow in the vane-less region of pump turbine from multiple perspectives. Chen [10] made experiment to research the visual flow characteristics for flow within low specific speed pump turbine model and won the "S" impeller flow between the image and the change of the velocity vector. And the "S" characteristics of the reasons of unstable flow are discussed and the wheel on vane-less region may be related to the formation of the "S" characteristics of the hydraulic instability phenomenon. In order to facilitate the observation, the shroud of the impeller was cancelled in the experiment. Nevertheless, the study on the internal flow characteristics of the impeller is still of great reference value. Petersen [11] studied the rotational stall in the "S" region of the pump turbine, so as to explain the formation of the "S" characteristic in the working condition of the turbine. Hasmatuchi [12] made a detailed experimental study on the pressure pulsation in the starting condition of the pump turbine, and
concluded that the low-frequency pressure pulsation exists in the low-flow of the pump turbine, which may be caused by the rotation stall. Hasmatuchi[13] [14] also observed the flow characteristics between the impeller and the guide vane near the no-load condition by using high-speed photography and bubble ingestion method, and found that there was a rotating stall phenomenon at the blade inlet of the impeller, whose stall frequency was about 70% of the rotation frequency.

Although some scholars have also conducted relevant studies on the flow in the s-region, there is still no unified and authoritative conclusion on how to explain the s-shaped phenomenon. From the perspective of PIV flow field test, this paper studies the internal flow state of s-shape working condition in detail, and provides some valuable experimental references for the s-shape problem of pump turbine.

2. Experiment

2.1 PIV parameter on pump-turbine

The research object is a reduced pump-turbine, and the whole model includes the draft tube, impeller, guide vane, stay vane and spiral case, as shown in Figure 1. The number of impeller blades is 9 and the number of guide vanes is 22, as listed in Table 1.

| Table 1. Main parameters of the tested pump-turbine model. |
|----------------------------------------------------------|
| Impeller diameter at inlet (mm)                         | 530 |
| Impeller diameter at outlet (mm)                        | 250 |
| Impeller blade number Z1                                | 9   |
| Guide vane number Z0                                    | 22  |
| Maximum guide vane opening a (°)                        | 24  |
| Rotational speed (rpm)                                  | 900 |
| Height of guide vane (mm)                               | 37.6 |
| specific speed ns= np0.5/H1.25                          | 93  |

2.2 PIV structure on pump-turbine

The test device design the observation window on the head-cover of model pump turbine, and the PIV camera is loaded on the top of the head-cover to capture the fluid motion state under the observation window. A window is designed on one side of the volute to ensure that the laser emitted by the PIV laser enters the fluid, and the laser passes through the transparent fixed guide vane and the movable guide vane and enters the location of the vane-less area between the guide vane and the impeller. In order to ensure the shooting effect, transparent Windows are made of acrylic plexiglass. In order to ensure the transparency of movable guide vane and fixed guide vane, the manufacturing of guide vane
must adopt water grinding technology to ensure the processing accuracy. The laser beam passes through the fixed guide vane and the movable guide vane along the transparent window of the volute. In order to ensure the objectivity of test results, test parameters is 40m water head according to IEC regulations, and the transparent window must bear the pressure of 0.5Mpa.

The main test instruments include PIV laser, PIV camera, and model pump turbine and so on, as shown in Figure 1. The PIV laser was arranged near transparent window made by glass on spiral case and the camera resolution is 15 frames. The PIV camera is fixed on the hydro-static bearing and the camera is 50cm above the head-cover. And the view area is on the observation window and is positioned by two bolt labeled by green circle. And the view area can include two impeller blades and three guide vane blades.
2.3 PIV tracer particle

PIV test shows that the selection of tracer particles is a very important step, and tracer particles should have good follow-ability and reflectance. A variety of tracer particles, mainly including silica, titanium dioxide and hollow glass beads are contrasted in the experimental, as shown in Figure 2. Through the comparison of experimental results, it is finally determined that the hollow glass microspheres have the best test effect and can meet the requirements of the reflective and tracer particles.

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

![Figure 2. The PIV test tracer particle.](image)
3. Results and analysis

3.1 Installation and debugging of field test devices

According to the test conditions of PIV, the platform and support for the laser, lens group, CCD camera and other test equipment with fixed PIV system are built.

1. Fix the laser so that it shines the laser light on the measured area (as shown in Figure 3), and the laser height is located in the middle of the guide vane height.

2. Fix the CCD camera so that it can fully capture clearly the flow state of the measured area, as shown in Figure 1C.

![Figure 3. The PIV laser on the middle of guide vane height.](image)

3.2 Test conditions

Take a pumped storage power station as an example: under the working condition of turbine, the rated head of the unit is 656m, the maximum head is 695m, and the minimum head is 626m. Under the working condition of pump, the maximum head of the unit is 711m, and the minimum head is 661m. The motor is a reversible synchronous motor with a rated capacity of 375MW and a speed of 500r/min. The model impeller of the power station is tested in the following conditions.

(1) Many experiments are finished in this PIV test. There are 9 operating conditions in total at 3 hydraulic heads and 3 guide vane opening near the optimal operating condition of the turbine. There are the optimal working condition, rated working condition and 50% load working condition (minimum head) of the turbine within the operating range are three working conditions. There are 6 operating conditions near the critical region S of the turbine, and each operating point has 30 operating conditions.

(2) There are 5 operating conditions near the critical hump area, and each operating point has 30 operating conditions and the initial cavitation of pump has 5 working conditions.

In this paper, only the operating point of the four-quadrant curve is selected for description. Figure 4 shows the operating point of the four-quadrant curve with different guide vane opening. The test opening is 5.0°, 5.6°, 6.0°, 7.0°, 17.0°, 18.0°, 19.0° and 20.0°, as shown in Figure 4. The test results of 5.0° and 20.0° in the four-quadrant curve were selected for comparative analysis.
The guide vane opening 5° is selected for PIV experimental observation on the key points, as shown in Figure.5. The strong vortexes are seen on the reverse pump area and the turbine braking areas, such as working condition of A, B and C. It’s that strong vortex hinders the water from the active guide blade into the impeller area, caused the hydraulic pressure sharp rising, so as to make the differential pressure increasing before and after impeller. Then a reversal $N_{11}$-$Q_{11}$ curve showed a reversed s-shaped characteristics and resulting in one $N_{11}$ corresponding to two $Q_{11}$ one-to-many phenomenon which causes two point fluctuation and affects the stability of the unit. That is the phenomenon that the unit cannot be connected to the grid normally. The flow smoothness in the vaneless region at the working conditions D and E of turbine mode. In the working condition of the pump, the flow is smoothness in the vaneless area on working point H. However, in the area close to zero flow condition G, the existence of strong vortices leads to the occurrence of hump phenomenon and the generation of strong pressure pulsation. In the pump braking area, the strong vortex in the vaneless area at the working point F also impedes the water from the impeller to the guide vanes, resulting in a decrease in the pressure difference between the rear and after the impeller and $N_{11}$ increasing. Therefore, the curve in the pump braking area presents an s-shaped feature. And the vortex rotating direction is opposite to the turbine mode.
PIV flow field observation was conducted at the characteristic working condition points on the guide vane opening $20^\circ$, as shown in Figure 6. In the reverse pump zone I and the zero-flow condition J of the turbine, the vortexes are serious. A vortex exists in the flow passage in the vane-less zone. As there is both flow in the direction of the turbine and the flow in the direction of the pump, the two flows cross each other. In K and L conditions close to the no-load condition, one vortex developed into a double vortex distribution. As the turbine and pump two-way flow rub each other. The bigger vortex is caused by the turbine direction of the flow induced and the smaller vortex is caused by the pump direction of the flow induced. The turbine flow is smooth with few vortices. In the braking condition M, the vortex strength gradually decreases. Close to the zero flow condition point N of the pump, the phenomenon of double vortices continues to appear. Pump operating conditions O and P, the flow is smooth in the channel. In the transition process, after the turbine load rejection, the unit’s operating state from the turbine condition into no-load, no-load into the turbine brake, and then into the reverse pump area. From PIV test observation of internal flow field, it can be seen that from no load to the area where the reverse pump is located, strong vortexes exist. Therefore, it is easy to understand that some units show the pressure exceeds the guaranteed value on volute and draft pipe during the transition process.

Figure 5. The PIV test results on guide vane opening $5^\circ$. 

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Figure 6. Graph showing the flow field observation.
4. Conclusions

In this paper, the PIV experiment is carried out and the flow image in the pump turbine is obtained. This paper focuses on the observation and research of the flow phenomenon in the guide vane opening 5° and rated opening of 20° which affects the unit grid-connection and the increase of the volute pressure and the decrease of the pressure in the draft pipe during the transition process.

The inner flow images at two guide vane opening degrees are obtained. From turbine working condition to no-load working condition, and then to turbine braking and reverse pump working condition area, the vortex is full of vane-less area behind the guide vane and in front of the impeller, which is also the important reason why the unit cannot be connected to the grid normally and the pressure exceeds the standard. These phenomena between guide vane and impeller observed by PIV test are different CFD results.

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References
[1] Yin J L, Liu J T and Wang L Q 2010 Performance Prediction and Flow Analysis in the Vaned Distributor of a Pump Turbine under Low Flow Rate in Pump Mode. *J. Science China-Technological Sciences*, **53**(12) pp 3302-09.

[2] Martin C S and Horlacher H 1990 Conversion of pump-turbine characteristics at zero flow, locked rotor position and runaway condition, *Proc. Int. Conf. 15th IAHR Symposium on Hydraulic Machinery and Systems*, Belgrade.

[3] Sun J, Zhu Y X and Han Z X 2001 Improvement of low-head no-load stability of unit 1 of tian huang ping pumped storage power station. *J. Hydroelectric power*, **27**(6) pp 60-63.

[4] Yao Z, Bi H L and Zhuang X H 2015 Simulation and analysis of the transition process of guangzhou pumped storage power plant A. *J. hydraulic power generation*, **34**(3) pp 88-100.

[5] Xiao Q H 2015 Commissioning of pumped storage units in xianyou power station. *J. Dongfang electric review*, **29**(9) pp 48-52, 58.

[6] Zhou Q, Xia L S and Zhang C Z 2018 Pressure pulsation and impeller stress in the transition process of pump turbine load rejection. *J. Chinese journal of hydraulic engineering*, **49**(11) pp 1429-38.

[7] Wei B Z and Ji C Q 2010 Stability of rotor of high speed and large capacity electric motor -- lessons of rotor pole accident of unit 1 in huizhou pumped storage power station. *J. Hydroelectric power*, **36**(9).

[8] Qin D Q 2016 Accident analysis of unit dump 100% load test in baishan pumped storage power station. *J. Hydropower and pumped storage*, **2**(6) pp 8-12.

[9] Kurokawa J 2002 Transient axial thrust of high-head pump-turbine at load rejection. *Proc. Int. Conf. JSME annual meeting*, Lausanne.

[10] Chen D X and Xie H 2001 Internal flow in “S” characteristic zone of low specific speed water pump turbine. *J. Chinese journal of hydraulic engineering*, **32**(2) pp 76-79.

[11] Pettersen K, Nielsen T K and Billdal J T 2004 An Explanation to the Steep Speed-Flow Characteristics of RPTs. *Proc. Int. Conf. 22rd IAHR Symposium on Hydraulic Machinery and Systems*, Stockholm.

[12] Hasmatuchi V, Farhat M and Maruzewski P, et al 2009 Experimental Investigation of a pump-turbine at off-design operating conditions. *Proc. Int. Conf. 3rd IAHR meeting of the workgroup on cavitation and dynamic problems in hydraulic machinery and systems*, Brno.

[13] Hasmatuchi V, Roth S and Botero F, et al 2010 High-Speed Flow Visualization in a pump-turbine under off-design operating conditions. *Proc. Int. Conf. 25th IAHR Symposium on Hydraulic Machinery and Systems*, Timisoara.

[14] Hasmatuchi V, Farhat M and Maruzewski P, et al 2011 Experimental evidence of a rotating stall in a pump-turbine at off-design conditions in generation mode. *J. Fluids Engineering*, **113**(3) pp 1-8.