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Research Progress on Cavitation Characteristics and Performance Optimization of High-Head Reversible Pump-Turbine

Bolin Ji

School of Energy and Power Engineering, Xihua University, Chengdu, China
bolinji151@gmail.com

Abstract. On the background of the global sustainable development that makes pumped storage a force to move toward high-head applications, a systematic knowledge of the cavitation behavior of high-head reversible pump-turbines and incorporation of the program to maximize the cavitation process of the unit are important to the long-run safe, stable, and efficient success of equipment. Cavitation, being an ordinary hydraulic phenomenon, has always been a very fundamental bearing on the performance and safe working of reversible-type pump-turbines. Not only does it result in a huge decline in unit efficiency, but also structural damage, vibration and noise, it has a devastating affect on the service life of the unit. The present paper analyses and discusses the mechanism of cavitation initiation, growth, and collapse; cavitation properties under three operating systems including operation of a high-head reversible pump-turbine, turbine operating, and pump operating; effects of cavitation on units; and finally ways of how to optimize the performance of cavitation based on existing research on this topic both within the nation and internationally. It also seeks to give information that will be used in the future research and development of pumped-storage hydropower plants.

Keywords: Cavitation, High-head, Pump-Turbine, Computational fluid dynamics simulation

1. Introduction

Guided by the Sustainable Development Goals, China is actively building a new power system centered on renewable energy, with the installed capacity of wind power, photovoltaic, and other renewable energy sources continuing to expand. The core of the peak-shaving and valley-filling energy storage is the pumped-storage power plants, which are currently growing ever bigger and technologically advanced. In pumped-storage power plants, water is pumped into an upper reservoir with electricity during downturn periods which is released to form power during peak demand periods. The majority of the pumped-storage power plants operate reversible pump-turbines. These machines are important equipments. They are in use in big hydropower stations in China. The examples of such stations are Dunhua and Yantai. A pump-turbine is a special reversible pump-turbine. It transforms energy in two ways. It consumes electric power in order to pump water in the

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pump mode. When the water falls in the turbine mode, the water generates electricity. Its predominant parts are the runner and guide vanes.

The design of these machines is normally above 300 meters. Strong flow flow patterns are formed in the machine with a high head. It also results in regular cavitation. Cavitation is a physical phenomenon. Local water pressure reduces to the saturated vapor pressure. Then water is converted into bubbles. These bubbles go to penetrated regions. The bubbles burst lastly and discharge energy. Cavitation is associated with vibration and noise. It damages materials. It also reduces hydraulic effectiveness. Thus, scientists should investigate cavitation in high-head reversible pump-turbines. This work is beneficial to the machine design. It also increases the reliability of the machines.

Current research focuses on cavitation mechanisms. It also focuses on the optimization of cavitation performance. J Li et al. [1] reviewed the basic theories and influencing factors. Z Wang et al. [2] used numerical simulations. They showed the link between flow patterns and cavitation. Y Fan et al. [3] built a multi-objective optimization framework. Many studies have found facts about cavitation mechanisms and performance optimization. However, there is currently a lack of systematic, integrated research and optimization schemes specifically targeting high-head operating conditions.

This paper focuses on high-head reversible pump-turbines. It studies their cavitation characteristics and performance optimization. It explains the basic mechanisms of cavitation. It looks at the cavitation characteristics of these machines under high-head conditions. It shows the effects of cavitation on unit performance and structure. Finally, it reviews recent research on methods to optimize cavitation performance.

2. Cavitation mechanism and theoretical foundations

2.1. The mechanism of initial cavitation based on energy conservation

The fundamental mechanism of cavitation can be described using the Bernoulli equation and vapor pressure theory. For steady flow of an ideal fluid, the Bernoulli equation is:

$$z+\frac{p}{\rho g}+\frac{v^2}{2g}=C \tag{1}$$

As shown in Equation 1, z represents the local head (m); p denotes the hydrostatic pressure (Pa); ρ is the density of water (taken as 1000 kg/m³ at standard temperature); g is the gravitational acceleration; v is the fluid velocity (m/s); and C is the total head coefficient for the same streamline.

Reversible pump-turbines face fast fluid flow under high-head conditions. Their flow passages must handle this speed. Fluid moves fast near the leading and trailing edges of the impeller blades. This speed raises the kinetic energy. The law of conservation of energy explains the next step. The pressure energy drops as the kinetic energy rises. The local pressure can fall below the saturated vapor pressure for the water temperature. When this happens, the liquid undergoes a phase transition. It forms cavitation bubbles. Experts call this process primary cavitation. This critical pressure forms the base of cavitation research. It acts as the rule for finding phase change in numerical simulations [1].

In actual engineering practice, saturated vapor pressure is not a constant but is influenced by operating conditions. For pumped-storage power plants, units often operate under complex conditions such as high summer temperatures or frequent start-stop cycles, making the cumulative

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effect of water temperature significant. This behavior can be described by the Clausius-Clapeyron equation:

$$\ln\left(\frac{p_{v2}}{p_{v1}}\right)=\frac{L_v}{R_v}\left(\frac{1}{T_1}-\frac{1}{T_2}\right) \tag{2}$$

As shown in Equation 2, p_{v2} and p_{v1} represent the saturated vapor pressures (Pa) corresponding to temperatures T_1 and T_2, respectively; L_v is the latent heat of vaporization of water (2.26×10^6 J/kg at standard temperature); R_v is the specific gas constant for water vapor (461.5 J/(kg·K)). As water temperature rises, the saturated vapor pressure increases, making cavitation more likely to occur. J Li et al. [1] point out that an increase in water temperature raises the cavitation critical pressure; under identical hydraulic design conditions, cavitation is more likely to occur in high-temperature water.

2.2. Evolution and collapse model of cavitation

After cavitation occurs, the growth, contraction, and collapse behavior of cavities as they migrate with the fluid flow is described by the Rayleigh-Plesset equation. This equation establishes a second-order nonlinear relationship between the cavity radius R and time t:

$$\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2=\frac{1}{\rho}\left(p_v-p_\infty+\frac{2\sigma}{R}-\frac{4\mu}{R}\frac{dR}{dt}\right) \tag{3}$$

As shown in Equation 3, R is the cavitation radius, ρ is the fluid density, σ is the surface tension coefficient, p_v is the saturated vapor pressure, and p_∞ is the ambient pressure at infinity.

This equation reveals the evolution process of cavitation and the root cause of cavitation collapse damage. Cavities expand rapidly in low-pressure regions and contract violently as they enter high-pressure regions. Toward the end of the collapse, asymmetric pressure causes high-speed microjets to form. If this occurs on the surface of a blade, the water hammer pressure generated by the microjets can reach several thousand megapascals, directly impacting the metal material and causing damage [1].

3. Cavitation characteristics under high-head and bidirectional conditions

3.1. Cavitation characteristics under high-head conditions

High-head pumps and turbines have a very large pressure difference between the inlet and outlet of the runner.Compared with units operating at medium and low heads, Ning Nan et al. [4] found in their study of long- and short-blade units in the 750-meter head range that, under high-head conditions, the velocity gradient within the flow passage is greater and the pressure distribution is steeper. The cavitation zone in high-head units changes easily with the cavitation coefficient. The downstream water level drops sometimes. When this happens, cavitation inside the runner grows fast. It does not grow slowly in a straight line. At the critical state, cavitation clouds begin as small spots on the blade surfaces. They quickly become large sheets. These sheets reach into the middle of the flow passage. This event makes the open area for water smaller. G Li et al. [5] showed similar

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results. They studied low lift-to-drag ratios. They found that low-pressure regions on the trailing edge connect quickly. This connection completely changes the flow field structure.

3.2. Cavitation characteristics under hydroturbine operating conditions

In hydromotor operating conditions, the water flow exhibits centripetal motion. Under these conditions, the cavitation distribution demonstrates significant flow-dependent characteristics and positional stability. In high-flow-rate operating conditions, cavitation primarily occurs at the lower ring root of the suction surface of long blades. This is because this area is located on the inside of a bend in the flow path; during operation, it is subjected to the combined effects of centrifugal force and Coriolis force generated by the rotating impeller. Furthermore, due to its proximity to the lower ring wall, fluid separation is highly likely to occur, creating a low-pressure center. Under hydroturbine conditions, cavitation usually starts here. The bubbles move down the suction surface as the cavitation number drops [4]. W Yang et al. [6] studied low-flow conditions. They found that bubbles at the outlet edge grow. These large bubbles can block the blade outlet.

3.3. Cavitation characteristics under pump operating conditions

Water flow has centrifugal motion under pump conditions. This motion creates a complex flow field. Tao et al. [7] studied these pump conditions. They found a difference between incipient cavitation and critical cavitation. The best point for incipient cavitation is the design point. However, critical cavitation shows better results at partial load points. Li et al. [8] looked at the "S"-shaped characteristic region. They noted a close link between cavitation and hump instability. They calculated the head-flow rate curve with cavitation effects. This curve shows a clear positive slope in the hump region. This slope means that cavitation makes the machine less stable. Cavitation bubbles appear on the suction side of the blades in the hump region. These bubbles block the flow path. They reduce the open area for water. This blockage lowers the head and efficiency. H Ruan et al. [9] used experiments and simulations. They found that cavitation causes flow separation at low flow rates. This separation makes flow conditions worse in the "S" region. Z Wang et al. [2] showed how cavitation grows in the "S" region. It begins at the blade exit edge. Then, it moves upstream along the suction surface. This movement creates recirculation vortices. It forms a cycle of flow channel, blockage, and cavitation recirculation.

4. The multidimensional effects of cavitation on reversible pump-turbine

4.1. The effect of cavitation on unit performance parameters and operational stability

Cavitation breaks the flow field. This break changes the flow patterns inside the unit. These changes affect performance parameters. These parameters include efficiency and pressure pulsations.

Cavitation harms energy conversion efficiency. It ruins fluid dynamics and flow field structures. This damage causes a drop in efficiency. G Li et al. [5] studied high-head pump conditions. The inlet pressure drops to 0.65 atmospheres. Cavitation bubbles grow at this pressure. These bubbles fill half of the entire impeller flow passage. This growth lowers the operating efficiency of the unit. The cavitation number also drops. This drop makes the pressure difference between the front and back of the blades change. This change causes another drop in unit efficiency.

Cavitation also harms operational stability. Impeller cavitation causes a drop in head. This drop affects the hump characteristic [8]. Li et al. [10] studied the hump region. They used Large Eddy

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Simulation (LES) for this study. Cavitation appears and collapses in cycles on the suction side of the blades. This cycle changes the rotation frequency. It also changes the amplitude of pressure pulsations. Cavitation changes these parameters. These changes make the unit less stable.

4.2. The effects of cavitation on turbine structures

The immense internal energy generated during the operation of high-head reversible pump-turbine causes cavitation damage to components that is far more severe than in conventional units. J Li et al. [1] point out that the immense pressure generated when cavitation collapses in high-pressure zones can damage the surface of components. S Liu et al. [11] found in their study that the radial forces acting on the rotor under no-air conditions are several times greater than those under normal operating conditions. This subjects the rotor and other components to immense impact forces, making them highly susceptible to damage. G Xie et al. [12], in their study on the effects of cavitation and different guide vane openings on reversible pump-turbines, found that the turbulent flow patterns caused by cavitation within the unit can subject components such as the runner and tailrace pipe to immense pressure, which, in severe cases, can lead to unit vibration and abnormal noises.

5. Method for improving cavitation performance based on computational fluid dynamics simulation and structural optimization

5.1. Computational fluid dynamics simulation technology

With advances in computational technology, computational fluid dynamics (CFD) has become the primary method for simulating fluid flow. Given the wide variety of operating conditions, selecting the appropriate simulation model is key to accurately simulating real-world flow patterns.

RANS is the most common turbulence model. The SSTk-ω model is a type of RANS. It works well both near walls and far away. It easily shows flow separation in complex states. S Wang et al. [2] used the SSTk-ω model for pumps. They studied the "S" zone. They saw cavitation move backward from the blade exit. They also saw the backflow it caused. Tao et al. [7] also used this model for pumps. They found a special event. The best conditions for initial cavitation and critical cavitation are different. These ranges do not match.

The LES model is another choice. It directly shows large turbulent structures. It captures turbulence details clearly. People created the MSST-PANS model to balance accuracy and computer speed. The MSST-PANS model is more accurate than the older URANS model. It predicts cavitation volume and pressure pulsations better. It also uses less computer time than the LES model.

As for the selection of cavitation models, the Zwart-Gerber-Belamri (ZGB) model is currently the most widely used tool. The ZGB model uses better formulas for bubble generation and collapse. Because of this, it clearly shows cavitation cloud detachment and unsteady flow. It is particularly suitable for simulating cloud-like cavitation in high-head units, ensuring the reliability of both simulation and structural optimization [2, 8].

5.2. CFD-based optimization strategies and structural optimization

CFD technology guides modern water engineering design. Researchers want to reduce cavitation damage. They also want to make machines work better. Therefore, they use CFD tests and optimization methods. These tools help them find the best designs.

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Today, single-objective optimization is not enough. Y Fan et al. [3] built a multi-objective optimization framework. They changed the blade layout and pitch angle. This change balanced machine efficiency and the critical cavitation coefficient. This method improved the impeller's efficiency. It also raised the lowest pressure on the blade surface. Furthermore, it made the cavitation-free operating region larger. Ruan et al. [13] also used multi-objective strategies. They used the NSGA-II algorithm to optimize the gradient angle distribution.

The 3D inverse problem design method is a basic tool for multi-objective optimization. This method uses a few parameters to control complex blade shapes exactly. Liu et al. [14] created a new way to design blade shapes. They made this for 800-meter class ultra-high-head machines. They controlled the surface mesh, blade loads, and blade distribution patterns. This method improves flow characteristics directly. It creates a structure that meets flow dynamics rules.

Engineers have created many new structures in recent years. These structures use the strategies above to stop cavitation in high-head reversible pump-turbines. Ruan et al. [13] solved a big problem. Pumps and turbines need different cavitation performance. They optimized the blade wrap angle distribution. This step smoothed the pressure gradient inside the flow passage. N Ning et al. [5] added short blades to the flow channel. This addition lowered the cavitation volume fraction from 8.2% to 3.5%. This drop reduced cavitation resistance. Xue et al. [15] designed guide vanes with horizontal blades. These flat blades broke the conditions for vortex formation. This design lowered the pulsation amplitude by 92.5%. It solved the flow problem from the source.

6. Conclusion

Against the backdrop of the global push toward renewable energy, pumped-storage power plants are playing an increasingly vital role in the power grid. The velocity of the flow however accelerates with the increase in design head of a turbine unit, and this is likely to lead to cavitation and jeopardize the safety of operations in such a unit. This paper conducts the review of the recent studies on the mechanisms, impact, and optimization of cavitation concerning the intention to offer a theoretical background on issues on the matter and the manner of improving the working stability of turbine units. The key conclusions are as follows:

(1) The high flow velocity in high-head conditions will result in a pressure drop, and the work of the unit will increase the temperature of water, the two factors will raise cavitation.

(2) Cavitation propagates in the outlet of the impeller in the shape of "S-shape of the pump performance curve towards the inlet. The bubbles of cavitation fill the flow direction and cause vortices, resulting in a strong reduction in head and efficiency in extreme cases, the flow can be discontinued.

(3) Cavitation results in a drastic change in pressure, as well as the imbalance in the distribution of stress. In deep cavitation the pressure pulsations within the unit increase, and radial forces on the impeller peak. Such recurrent effects and the asymmetrical distribution of stress are the major contributors of component fatigue failure.

The best solution to the problems is to conduct a structural optimization with the help of computer simulations, which will reduce the impact of cavitation in the source, through the optimizing of the design of the blades or guide vanes.

The cavitation problem may decrease efficiency, decrease the service life of units and also raise the maintenance costs. The poisonous impact of cavitation should be considered in the future designs. It is only through such accomplishments as that of surmounting the problem of cavitation in high-head pump-turbines, that the safe and stable long-term functioning of power plants worked by pumped-storage can be guaranteed.

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