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The research and test of the cavitation performance of first stage impeller of centrifugal charging pump in nuclear power stations

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ABSTRACT

The safety production is the most important index for nuclear power development, and the CVCS (chemical and volume control system) occupies an important place in safety control system. The CCP (centrifugal charging pump) is an important component of CVCS system and its particularity decides the high requirements on the cavitation performance, so the research on CCP cavitation has great significance. Using the 3D Pro/E software, the paper makes models of the flow passage components of first stage prototype of CCP in nuclear power stations, and completes the cavitation steady-state computation in the case that the high flow rate of first stage prototype reaches $Q = 160\,m^3/h$ using the numerical computation software ANSYS CFX. The cavitation is divided into the following five stages according to its development process: inception operating condition, development operating condition, critical operating condition, serious operating condition and fracture operating condition. The research analyze the flow field, static pressure fields and bubble distribution conditions in the impeller in different cavitation states, and selects the middle flow line, the front shroud flow line and the back shroud flow line from the same blade for the comparative analysis; to verify the reliability of computation, the researcher made a first stage cavitation prototype to verify its hydraulic performance and cavitation performance. After the comparative analysis on the flow field, pressure and bubble distribution conditions of CCP first stage impeller in different cavitation states, the research draws the following conclusions: (1) as the inlet pressure decreases, the cavitation degree increases, the bubble distribution area extends from impeller inlet to impeller outlet and shows different laws in different cavitation states; (2) the generation of cavitation is affected by the pressure changes in impeller passages, and when the inlet pressure decreases, the static pressure in impeller passage decreases, thus producing a local low-pressure area; (3) the comparison of computation and test results shows small errors, thus proving the accuracy of analog computation; besides, the research verifies the cavitation performance in different flow rates by test, and test results show that $NPSH_3$ is smaller than the 7.8 m stipulated in *Technical Specifications* in any flow rate condition, indicating that the design is reasonable. The research points out a direction for the further improvement of optimization design of CCP cavitation performance.

Different from ordinary hydropower stations or thermal power stations, nuclear power stations have strict requirements on design and production, and the most important index for nuclear power development is safety production. Therefore, the design of safety system is of great importance. The chemical and volume control system (CVCS), as an important component of safety system, plays an important role in the safety control system. In this case, centrifugal charging pump (CCP), an important component of CVCS, with safety level II and quality grade QA2, has great research significance (Pang et al., 2010).

Centrifugal charging pumps which are used in pressurized water reactors (PWR) are critical to nuclear plant operations (Zhang et al., 2014a). The particularity of CCP requires it can operate safely and reliably in various operating conditions. In different operating conditions, the charging water comes from different sources. In the charging condition, the charging water comes from volume control tanks or water storage tanks; in the high head safety injection condition, the charging water comes from low head safety injection pump outlets or reactor plant pits and refueling water tanks. Therefore, CCP must have good cavitation performance to adapt

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to different inlet conditions. The Technical Specifications of CCP requires that the maximum pump efficiency $\eta \geq 60\%$, the maximum power $P \leq 650$ kW, and the cavitation allowance NPSH3 ≤ 7.8 m in the case of the maximum flow rate of 160m^3/h. Therefore, the research on CCP's cavitation performance has great significance. The phenomenon of the rapid formation and subsequent collapse of gas or vapor bubbles in a flowing liquid is called cavitation (Suzuki, 2007). Cavitation can lead to lower performance and efficiency, besides, physical damage, vibrations and noises usually occur concomitantly (Cernetic and Cudina, 2011). To reduce the effects of cavitation, we need to deepen the understanding of the physical phenomena constantly (Bachert et al., 2010). The research work about the effect of the blade leading edge angle on the pump cavitation is still limited (Kyparissis and Margaris, 2012). There still exist many misunderstandings regarding air, cavitation, cavitation noise, and the cavitation damage in centrifugal pumps (Budris, 2009).

In nuclear power stations, pumps are used widely in circuits and systems as general equipments, and their safe, reliable and stable operation plays a vital role in the safe operation of nuclear power stations, but the appearance of cavitation will impact the safe operation of pumps seriously, so the research on the pump cavitation in nuclear power stations has great significance (Zhu et al., 2012; Wang et al., 2013).

There is much research about cavitation in centrifugal pumps till now. In 2005, through analyzing the results from acoustic emission, Alfayez got a clear relationship between AE activity measured from pump casing, suction and discharge pipes, and incipient cavitation (Alfayez et al., 2005). In 2007, using the presented cavitation prediction, Jun Li observed the flow characteristics trends associated with off-design flow and twin cavities in the blade channel (Li et al., 2007). In 2010, Harihara presented a brief overview of a model-based fault detection system, which is used to detect the onset of cavitation in centrifugal pumps. This system avoids using any mechanical sensors on either the pump or the motor (Harihara et al., 2010). In 2011, Ahonen put forward a novel method for detecting cavitation in a centrifugal pump by a frequency converter (Ahonen et al., 2011). In 2014, an alternative method to detect the phenomenon of cavitation in centrifugal pumps was developed by Stopa. This method is based on a load torque estimation which is simple to fulfill and needs only measurement of motor variables (Stopa et al., 2014). In 2014, Zhu mentioned a method to detect and grasp the unsteady scale flow structures, which are verified by the flow around an equilateral triangular cylinder and proved effectively by the cavitation flow in centrifugal pumps (Zhu et al., 2014). In 2014, Bidhandi found that cavitation initiation can be delayed by SiO2 nanoparticles, and the cavitation growth rate can be notably be decreased (Bidhandi et al., 2014).

The paper analyze the flow field and bubble distribution situations in passages in CCP first stage impellor in different cavitation states, and thus provides a direction for the further optimization design of cavitation performance.

1. Introduction to CCP in nuclear power stations

The CCP of nuclear power station is an important composition of CVCS in the primary circuit of nuclear power station, having the following functions: (1) CVCS charging function: to supply charging water to the reactor coolant system when the nuclear power station starts, operates and shuts down amplifier, in order to keep a correct liquid level in the pressurizer and control the fluctuations of water level in the pressurizer; (2) seal water injection: to inject cooling water in the primary seal of reactor coolant pump, to prevent hot coolant leaking from the seal and ensure the normal work of seal; (3) high head safety injection: to act as a safety injection pump in the loss of coolant accident and run with a high flow rate of 148–160 m^3/h to discharge heat from reactor in a short time and prevent the exposure of reactor core in the accident.

Table 1
Main parameters of first stage impeller.

Physical quantity	Symbol	Unit	Value
Specific speed	n_s	/	74.5
Impeller inlet Dia.	D_j	mm	154
Impeller outlet Dia.	D_2	mm	236
Number of blades	Z		4
Impeller outlet width	b_2	mm	12

2. Design of charging pump

For the reasons above, the research completes the design of the CCP first stage impeller, and optimizes it and then completes the hydraulic design of first stage impeller. Table 1 shows the parameters of first stage impeller of CCP.

3. Numerical computation

3.1. Model building

According to the actual structures of CCP prototype and engineering prototype, it can be seen that the first stage flow passage components include the annular suction chamber, the first stage impeller and the double-flow-passage guide blade. Considering that the main components affecting cavitation are in the suction chamber and the impeller, and the double-flow-passage guide blade has less influence on cavitation, the researcher changed the double-flow-passage guide blade into a double-volute structure when researching the first stage impeller, since both of them have double flow passages and a similar structure. To reduce the impeller modeling error, the research adopts the impeller drawing method proposed in literature (Dai et al., 2004), and uses the Pro/E 3D modeling software for the precision modeling of impeller according to the parameters of optimized impeller. Fig. 1 shows the 3D models built according to related parameters of annular suction chamber and double-volute structure.

3.2. Mesh generation

The paper adopts the Mesh module in ANSYS Workbench for mesh generation. In the premise of ensuring mesh precision and computation accuracy, the research uses the automatic mesh generation method for the mesh generation of the part of water to be computed; besides, the research makes the encryption processing to impeller mesh and the matching processing to the mesh at the interface. And, the research also makes an independence check of mesh. Fig. 2 shows the mesh of flow passage component assembly. The numbers of grids of annular suction chamber, first stage impeller and double-volute structure are 607020, 649511 and 1144102 respectively.

3.3. Boundary conditions

The paper adopts ANSYS CFX software for computation, analyze all the turbulence models and cavitation models involved in the CFD numerical computation by consulting existing literatures, and finally, considering CCP's characteristic of low specific speed and according to literatures, selects the SST turbulence model and the Zwart–Gerber–Belamri cavitation model and adopts the second-order upwind scheme and the SIMPLEC algorithm based on the fully-implicit coupling algebra multi-grid method. To realize the