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Study on the complete rotational characteristic of coolant pump in the gas-liquid two-phase operating condition

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ABSTRACT

One of the most serious accidents of reactor coolant pump was the loss of coolant accident (LOCA) which may happen in any part of component of reactor system or coolant liquid circulation pipe. During the accident, the pump will be in a gas-liquid two-phase mixing operating state. The paper researches the full-flow hydraulic characteristics of forward rotation and reverse rotation of reactor coolant pump in the gas-liquid two-phase operating condition, respectively, in many operating conditions, such as the forward-rotation positive-flow, the forward-rotation negative-flow, the reverse-rotation positive-flow and the reverse-rotation negative-flow, and analyzes the laws of gas volume distribution in the overall fluid area with different gas fractions in different operating conditions using CFX analog computation method. The research finds with different gas fractions, the reactor coolant pump's torque complete-characteristics curve and head complete-characteristics curve show basically the same changing laws, i.e., the pump's operating torque was directly proportional to water head, and when the two-phase flow's gas fraction reaches 0.40, the pump's safe flow interval was only $0.087Q_0$, basically losing the ability carrying safe flow to reactor core; in different gas fraction conditions, the homogeneous distribution of gas phase component in the fluid area was mainly related to the operating condition of pump, and when the volume flow rate deviates from the designed operating point, the fluid medium's gas phase and liquid phase will separate to some extent, and in the same operating condition with different gas fractions, the distribution of gas fractions in the fluid area shows basically the same laws.

The nuclear industry and nuclear research institutions focus on the understanding on the security mechanwasm and the reliability in the case of accident. Some imaginary unforeseen circumstances may cause the core interruption and radioactive leakage. One of the most serious accidents was the loss of coolant accident (LOCA). The LOCA refers to the accident of the leakage of a part of or most coolant due to the crevasse or fracture of primary circuit pressure boundary. The fracture in the heat pipe section of main pump may cause a LOCA, and when the size of crevasse was big, the main pump will go through a transient transition process from the pump operating condition to the braking condition in a short time, accompanied with the gradual decrease in flow; when the crevasse was in the cold pipe section in a big size, the main pump will go through a transient transition process of sudden increase in flow in a short time. Therefore, in the accident condition, the reactor coolant pump may suffer from halt, runaway or braking.

However, when the LOCA discharge stage happens continuously, there were two stages: the sub-cooled depressurization and the saturated depressurization. Because the medium was lost from the crevasse, the sub-cooled depressurization stage lasts for a short time, and the system pressure decreases to the partial saturation pressure of fluid within 5–100 ms; in the saturated depressurization stage, the fluid flashes and the coolant starts boiling, presenting a vapor-liquid two-phase flowing state, resulting in the continuous depressurization at a much slower rate. The vapor-liquid two-phase flow starts from the upper reactor core of boiling frontier and the hottest position in upper chamber and spreads to the whole primary coolant circuit. Because in the saturated depressurization stage, the primary coolant circuit system still has the pressure big enough, the flow passing the crevasse will be accompanied with the vapor-liquid two-phase critical flow. The complicated vapor-liquid two-phase flowing state presented by the reactor coolant pump in the LOCA makes the running condition of main pump deteriorate and even make the main pump lose the function of cooling reactor core. Generally in the normal operation period, there were only liquid flow, single phase Analysis and

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characteristics curve for pump. However, during the accident, the pump will be in the two-phase-mixing running state accompanied with halt, runaway and braking.

Many foreign and domestic scholars have predicted the performance of reactor coolant pump in the accident condition. Shuliang Huang made a model of AP1000 power plant system and creator core, made a complete LOCA DNB Analysis based on the transient parameters of complete LOCA given by the TRACE program and found that in the transient process, the DNBR (departure from nucleate boiling ratio) in creator core was always higher than the limit of safety Analysis and met DNB design datum (Shuliang et al., 2015); Peng Guo and Yun Long predicted the unsteady flow in the pump when the reactor coolant pump suffers the LOCA through experiments with simulation, and found that because the outlet of pump case was in the center of pump case, the main flow following the rotation direction of impeller had friction and collwasions with the fluid in the outlet, thus causing the loss of energy and resulting in the uneven distribution of inner flow field, in which case the main pump ran with a small flow, producing the unsteady flow and even causing the vibration of pump (Peng et al., 2016; Yun et al., 2014; Long et al., 2016); Peng Wang and Qiang Fu simulated and optimized the reactor coolant pump's impeller shaft eccentricity, the impeller inlet's edge position and the matching relation between the impeller and the diffuser, respectively, and analyzed the unsteady transient characteristics of reactor coolant pump in the two-phase flow condition (Peng et al., 2015; Qiang et al., 2016; Qiang et al., 2015; Fu et al., 2016); Rongsheng Zhu and Xiuli Wang researched the dynamic characteristics of reactor coolant pump in the cavitation condition through CFD simulation and experimental verification, and found that the position with the maximum gas volume fraction in the cavitation area corresponded to the part of blade inlet with the maximum deformation (Rongsheng et al., 2016; Xiuli and Yonggang, 2015); Ruihua Liu and Yonggang Lu researched the gas-liquid two-phase experiment of pump, defined different operating conditions of pump in the four-quadrant experiment, and introduced the composition of experimental setup and experiment procedure in four quadrants (Ruihua et al., 2015; Lu et al., 2017; Zhu et al., 2017). Yun Long mainly researched the unsteady characteristics of reactor coolant pumps with non-uniform inflow and Especially in the aspect of pressure pulsation (Long et al., 2017; Yun et al., 2017; Long et al., 2016).

The research results published by scholars show that few studies have been made on the complete characteristics of the gas-liquid two-phase flow when the reactor coolant pump was vaporized in the cooling medium except the researchers of research groups. The paper mainly researches the pump hydraulic performance, the gas volume distribution in flow passages and the flow state of fluid of reactor coolant pump in the forward-rotation and reverse-rotation full-flow operating conditions with different gas fractions, and offers reference for the prediction of the hydraulic performance of reactor coolant pump in the LOCA condition through CFD simulation Analysis and experimental verification.

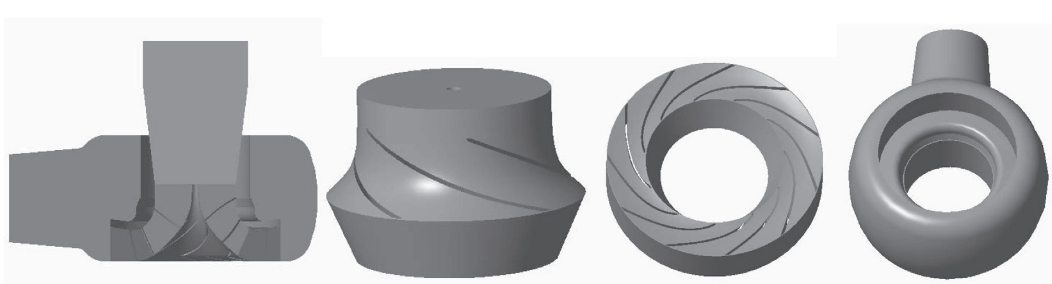
1. Calculation model

In this manuscript, the forward and reverse full-flow characteristics of reactor coolant pump under gas-liquid two-phase conditions with gas fraction of 0.05, 0.1, 0.2, 0.3 and 0.4 respectively were studied. The matching plan for reactor coolant pump's impeller and diffuser was the combination of 5 impeller blades and 11 diffuser blades. 3D modeling Software Pro/E was used to built the water body. The whole model was composed by five parts: the inlet section, the water body of impeller, the water body of diffuser, the water body of volute and the outlet section, as shown in Fig. 1. Main parameters of main pump were shown in Table 1.

2. Mesh generation and boundary conditions

2.1. Mesh generation

The meshing Software ICEM-CFD was used to mesh each fluid domain and the hexahedral structure meshes was adopted as shown in Fig. 2. To ensure the accuracy of meshes' simulation of reactor coolant pump, it was needed to examine the independence of model grid. Table 2 gives the relation between reactor coolant pump's efficiency and mesh quantity in different mesh divisions. The mesh was the computing element of CFX, so the quantity and quality of mesh have great influences on computing accuracy



(a) (b) (c) (d)

Fig. 1. Physical model of the main pump: (a) assembled domain, (b) impeller, (c) diffuser, and (d) volute.

Table 1
Main parameters of the CAP1400 reactor coolant pump.

Geometric parameters			Pump design condition		
Impeller inlet diameter, D_1	mm	648	Flow, Q_0	m3/h	21642
Impeller outlet diameter, D_2	mm	761	Head, H_0	m	111.3
Impeller outlet width, b_2	mm	219	Speed, n	r/min	1480
Impeller wrap angle, φ	o	73	specific speed, n_s	–	386.5
Diffuser inlet diameter, D_3	mm	776	Test speed, n_1	r/min	1460
Diffuser outlet diameter, D_4	mm	233	Test head, H_t	m	108.5
Diffuser wrap angle, φ_2	o	52			