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Original Article

Particle image velocimetry measurement of complex flow structures in the diffuser and spherical casing of a reactor coolant pump

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A B S T R A C T

Understanding of turbulent flow in the reactor coolant pump (RCP) is a premise of the optimal design of the RCP. Flow structures in the RCP, in view of the specially devised spherical casing, are more complicated than those associated with conventional pumps. Hitherto, knowledge of the flow characteristics of the RCP has been far from sufficient. Research into the nonintrusive measurement of the internal flow of the RCP has rarely been reported. In the present study, flow measurement using particle image velocimetry is implemented to reveal flow features of the RCP model. Velocity and vorticity distributions in the diffuser and spherical casing are obtained. The results illuminate the complexity of the flows in the RCP. Near the lower end of the discharge nozzle, three-dimensional swirling flows and flow separation are evident. In the diffuser, the imparity of the velocity profile with respect to different axial cross sections is verified, and the velocity increases gradually from the shroud to the hub. In the casing, velocity distribution is nonuniform over the circumferential direction. Vortices shed consistently from the diffuser blade trailing edge. The experimental results lend sound support for the optimal design of the RCP and provide validation of relevant numerical algorithms.
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1. Introduction

The reactor coolant pump (RCP) is one of the most important components of a nuclear power plant. It delivers coolant to enable heat exchange between the core of the reactor and the steam generator [1,2]. The RCP is the only piece of equipment that is required to rotate at high speed and for long operation period in the nuclear island. The operation of the RCP is related to the safety and stability of the whole nuclear power plant. Moreover, the operation of the RCP is sustained with a considerable amount of power. Regarding the practical application of the RCP, the operation stability should be granted the highest priority [3–5]. Meanwhile, a wealth of research work has been dedicated to the improvement of the performance of the RCP [6–8].

The external performance of the RCP depends significantly on the internal flows involved. Moreover, both optimization of the geometry of hydraulic components and development of a flow control scheme necessitate good understanding of the flow patterns in the RCP. However, quantitative flow information and generalizable conclusions about the flow structures of the RCP are scarce. The majority of published work employed the computational fluid dynamics technique. Ni et al. [9,10] studied the unsteady flow structures and pressure pulsations in the RCP using the large eddy simulation method. Wang et al. [11] numerically investigated the vapor–liquid two-phase flow in model pumps. Gao et al. [12] analyzed transient flows inside the RCP during flow coastdown period based on computational fluid dynamics results. As the most vital pump part, the RCP casing is spherical in shape to ensure the reliability and stability of pump operation. In consideration of the unique geometry of the casing, the flow structures inside are appreciably intrinsic. However, measurement of flows in the RCP has not been reported so far. Meanwhile, even from a numerical aspect, the depiction of highly three-dimensional flow structures in the RCP has not been attained.

Optimal measurement techniques such as particle image velocimetry (PIV) are sufficiently dependable in revealing flow structures associated with fluid machinery [13]. PIV investigations have been undertaken to study the flow field in impeller pumps. Jens et al. [14] used PIV to measure the internal flows of a 2D centrifugal pump at high flow rate. The influence of the blade–tongue interaction on local flow patterns was illustrated. Shao Chunlei et al. [15,16] analyzed the difference between the PIV

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and numerical results with respect to a molten salt pump. Miyabe et al. [17] measured flows near the diffuser inlet using PIV techniques and proposed that the back flow to the impeller near the diffuser inlet triggers the occurrence of rotating stall. Inoue et al. [18] and Lu et al. [19] used PIV to visualize the flow field in the impeller of a mixed flow pump and to capture the jet-wake phenomenon near the impeller outlet. In most of the published literature about flow measurement for impeller pumps [20–22] explaining flow patterns in pumps through velocity and vorticity distributions has proven effective and can provide an intuitive reference for the optimal design.

To reveal the flow structures in the spherical casing and outer part of the diffuser of an RCP model, the PIV technique is employed in the present study. Velocity and vorticity distributions for design and off-design flow rates are obtained. Local flow patterns near the discharge nozzle of the casing are described. Velocity distributions at different cross sections are analyzed in detail as the flow rate varies. The experimental results are compared with the published numerical results. Besides this, flow patterns at different regions in the RCP are compared. Both velocity profile in the diffuser outlet and vorticity distribution near the diffuser blade trailing edge are presented. It is anticipated that this study will provide sound support for internal flow control, optimal design of the RCP, and the validation of relevant numerical schemes.

2. Experimental facility and measurement techniques

2.1. Experimental facility

An RCP model was devised to fulfill the requirements of flow measurement, as shown in Fig. 1. The main design parameters of the model pump are listed in Table 1. The RCP model tested in the experiment is a scaled model; the dimension scale is 1:3 with respect to the prototype. The values of the quantities listed in Table 1 were obtained based on similarity principles. To realize noncontact optical measurement, the laser must penetrate into the target flow region. Therefore, the suction duct, diffuser, and spherical casing of the model pump were made of plexiglass, as shown in Fig. 2. A copper impeller was used. At the same time, to increase the accuracy of optical measurement, a water jacket was mounted surrounding the casing to compensate for the refractive index.

The experiment was carried out on a closed-loop test rig, which conforms to the ISO 9906 standard, as shown in Fig. 3. This loop incorporates a water tank with volume of 11.6 m^3. The accuracy of

Table 1
Main design parameters.

Parameter	Value
Nominal flow rate Q_N	848 m^3/h
Design head H_N	12.7 m
Nominal rotational speed n	1,480 r/min
Nominal flow rate at 900 r/min Q_d	515.5 m^3/h
Impeller inlet diameter D_1	221 mm
Impeller outlet diameter D_2	268 mm
Impeller outlet width b_2	84 mm
Diffuser inlet diameter D_3	298 mm
Diffuser outlet diameter D_4	459 mm
Diffuser outlet width b_3	71.4 mm
Casing diameter D_5	637.5 mm
Impeller blade number Z_i	4
Diffuser blade number Z_d	12

Fig. 2. The transparent plexiglass casing and diffuser.

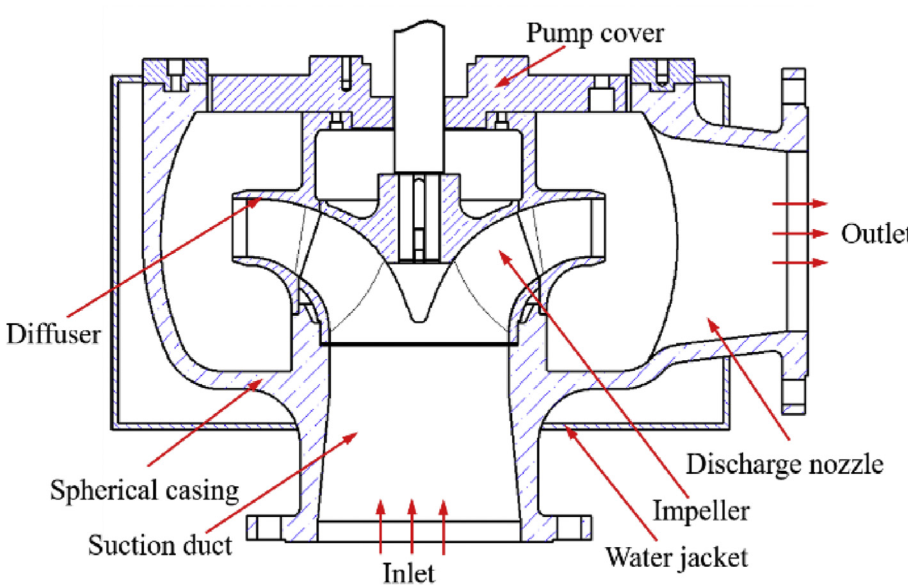

Fig. 1. The RCP model.
RCP, reactor coolant pump.

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