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Effects of rotating speed on the unsteady pressure pulsation of reactor coolant pumps with steam-generator simulator

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ABSTRACT

Non-uniform suction flow is generated at the inlet of the reactor coolant pump due to the complex geometry of the steam-generator simulator. From our previous work, the non-uniform inflow has a great effect on the flow structures in the pump. The unsteady pressure pulsation characteristics in a reactor coolant pump with steam-generator simulator are investigated in various flow rates and various rotational speeds. Pressure pulsation signals measured from the sensors on the pump casing and outlet pipe are analysed by FFT (Fast Fourier Transform) and RMS (Root Mean Square) method. Pressure pulsation characteristics, both discrete peaks and RMS values, are easily affected by different operational conditions and measuring positions. Pressure amplitudes at f_{RPF} increases with rotation speed increasing in different flow rates, but pressure amplitudes at f_R and f_{SPF} fluctuate slightly with the rotation speed increasing. Meanwhile, the effect of rotational speed on pressure pulsation are analysed. It is found that pressure amplitudes of RMS value and f_{RPF} increase with rotating speed increasing. This means that low rotating speed will reduce the pump vibration, so adjusting rotating speed is an appropriate method to stable operation of the pump. Finally, the present work will provide a different view on the pressure pulsations in the pump with non-uniform inflow in different rotation speeds. This research is helpful to provide a good reference for non-uniform inflow study of the pump, and it is helpful to the vibration analysis and fault diagnosis of the pump.

1. Introduction

The reactor coolant pump is one of the most important equipment in the nuclear power plant. In the Advanced Pressurized Water Reactor (APWR) primary coolant system, two canned motor pumps are directly attached to the cold side of the steam generator (Sun et al., 2010), as shown in Fig. 1(a) and (b). The pumps are identical designed based on the performance under uniform inflow with the straight pipe (Long et al., 2016; Long et al., 2016). However actual non-uniform suction flow is generated in the discharge pipe of the steam generator due to the complex geometry in the steam-generator simulator, and it would affect the pumps performances (Cheng et al., 2014). Due to rotor–stator interaction, unsteady pressure pulsation has a direct impact on the stable and safe operation of pumps (Brennen, 1994). The pressure pulsations of the pump, as a boundary condition of reactor system, is usually a significant scientific issue.

Up to now, only few researchers have studied the effect of the non-uniform inflow on the performance of the pumps. The performance of a mixed-flow pump and hydrodynamic forces on the impeller under non-uniform suction flow are investigated with experimental method by Van Esch (2009), it is found that the performance of the pump is influenced by the type of suction velocity profile and a considerable steady radial force appears when the suction flow is non-uniform. The flow patterns of non-uniform flows in a rectangular open suction passage is studied using 2-D PIV (Two-Dimensional Particle Image Velocimetry) method (Xu et al., 2005), which gives velocity vectors in two directions on the plane by cross-correlation analysis of the fluorescent particles in the shooting plane of the flow channel. The flow characteristics within the connection between the steam generator steam-generator simulator and the pump suction are investigated by experimental method (Huang, 2002), and it is found that axial vortex is eliminated and axial velocity is uniform in the outlet section in the nozzle of the steam-generator simulator. But the interaction between the steam-generator simulator and the pump has not been investigated since no pumps are connected to the steam-generator simulator in the test loop. The effect of the velocity distortion generated by the steam generator on the performance of the two pumps is investigated by CFD method (Cheng et al., 2014), and the results suggest that the nozzle dam brackets should be installed in the outlet pipe of the steam generator.

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Nomenclature

D_2	impeller outlet diameter, 160 mm
b_2	impeller outlet width, 67 mm
η	efficiency
p	pressure, Pa
Δp	pressure changed, $\Delta p = p - \bar{A}$, Pa
$\bar{A}$	mean amplitude of the pressure, Pa
ΔH	pressure fluctuation described as the water column, $\Delta H = \Delta p/\rho g$, m
P	water density, 1000 kg/m^3
f_R	rotating frequency of impeller blade, n/60, Hz
f_{RPF}	rotor passing frequency, $Z_1 f_R$, Hz
f_{SPF}	stator passing frequency, $Z_2 f_R$, Hz
Z_1	number of impeller blade, 4
Z_2	number of diffuser blade, 5
Q	nominal flow rate, 280 m^3/h
H	nominal head, 6.53 m
n	nominal rotating speed, 1800 r/min
Q_{opt}	operational flow rate, m^3/h
H_{opt}	operational head, m
n_{opt}	operational rotating speed, r/min
P	power of the pump
n_s	specific speed, $n_s = 3.65ndQ^{0.5}/H^{0.75}$, 445.51
FFT	Fast Fourier Transform
RMS	Root Mean Square

Lots of investigations have been carried out to study the unsteady flow, and Fast Fourier Transform (FFT) method has been proved to be the most effective tool to analyse pressure fluctuations characteristics (Barrio et al., 2008; Barrio et al., 2010; Benra, 2006; Li et al., 2015; Parrondo-Gayo et al., 2002; Pei et al., 2012; Pei et al., 2013; Toussaint, 2006; Wang and Tsukamoto, 2003; Yao et al., 2011). Some studies focus on the influence of geometry on pressure pulsation by either experimental or numerical method (Spence and Amaral-Teixeira, 2009; Yang et al., 2012; Yang et al., 2014). Zhang et al. (Zhang et al., 2015) explored a slope volute pump to reduce the level of pressure pulsation and used numerical simulation to analyse its influence on flow structures. However, these researchers did not consider the effect of non-uniform inflow on pressure pulsations due to the complex geometry at inlet. Pressure pulsations in the casing and outlet pipe are significant input conditions for the design of the nuclear reactor. It is sorely necessary to research pressure pulsations of the pumps with steam-generator simulator.

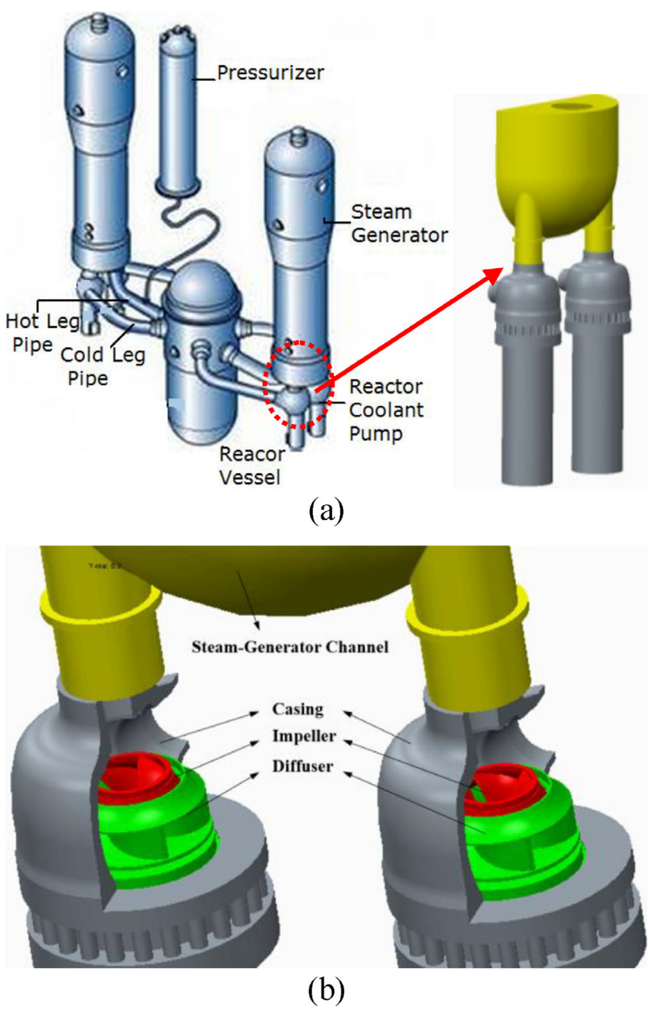

Fig. 1. Schematic diagram of connection type.

In our previous work, the effect of non-uniform and uniform inflow on the pressure pulsation has verified by numerical method (Long et al., 2016; Yun et al., 2017; Yun Long et al., 2017), and unsteady pressure pulsation spectral characteristics are investigated by experiment in various flow rates (Long et al., 2017). In the present study, unsteady pressure pulsation characteristics in a reactor coolant pump with steam-generator simulator are investigated in various flow rates and various rotational speeds. Pressure pulsation signals are obtained with seven fast-response pressure transducers mounted on the pump casing and outlet pipe. Detailed analysis of pressure spectrum is performed by Fast Fourier Transform (FFT) method, and special attention is paid to pressure pulsation peaks at blade passing frequency and some nonlinear interaction frequency components. Meanwhile, the influence of rotational speed on pressure pulsation is investigated.

2. Model pump and experimental system

2.1. The model pump

The model pump was homologous to the prototype, with a diffuser in the spherical casing. The tested model pump and its structure are shown in Fig. 2. The cold side of the steam generator has two discharging pipes, as shown in Fig. 1. Since the cold side of the steam generator is symmetric, it is assumed that the flow field inside is also symmetrical. So the steam-generator simulator could be divided into two mirror parts. The Steam-Generator simulator 3D model and its real dimensions are shown in Fig. 3. Firstly, at the outlet of the real steam generator entering to the channel head, the flow is uniform because of the many tube bundles arranged in the steam generator to control the flow. Secondly, the Steam-Generator simulator is designed to make the flow as uniform as possible by providing a pore plate in the channel head. The impeller has an outlet diameter of 160 mm with the other pump parameters listed in Nomenclature. The nominal flow rate $Q = 280$ m^3/h and the nominal head of the model pump $H = 6.53$ m.

2.2. Experimental system

A test rig is developed in order to investigate the pump hydrodynamics and pressure pulsations, as shown in Fig. 4. The tested pump is driven by a canned motor controlled by a frequency converter. The test rig is a closed circulation system equipped with calibrated equipment for various parameters including the flow rate, pressure, and power. Due to the non-uniform inflow, static pressure values are measured at the inlet and outlet of the pump by three differential pressure transducer, and the uncertainty is within ± 0.065%. The flow rate is