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Numerical investigation on the unsteady characteristics of reactor coolant pumps with non-uniform inflow

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HIGHLIGHTS

- The unsteady characteristics of the pumps with uniform and non-uniform inflow was researched.
- The difference of the performance and the pressure pulsation with different inflow are compared.
- Pressure pulsation signals are analysed using FFT, RMS and Peak-to-Peak Value method.
- The effect of non-uniform inflow on the radial force are analysed.

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ABSTRACT

The pumps are generally designed and are selected based on performance under uniform inflow with the straight pipe, but actually non-uniform suction flow occurs at the inlet of the reactor coolant pump due to the complex geometry in the channel head. It is sorely necessary to research the unsteady characteristics of the pumps with uniform and non-uniform inflow. In this paper, CFD approach is employed to analyse the inlet and outlet pressure pulsation characteristics of reactor coolant pumps with different inflows. The channel head induces non-uniform flow in the pump inlet, while straight pipe is with the uniform inlet flow. Meanwhile, the pressure pulsations at positions of the inlet and outlet with different inflows are investigated. And pressure pulsation signals are analysed using *FFT*, *RMS* and Peak-to-Peak Value methods. The differences of the pressure pulsation and its characteristic between the channel head and straight pipe at the inlet and outlet are obvious due to the different inflows of channel head and straight pipe. The pressure amplitudes of f_R, f_{RPF}, $2f_{RPF}$, $3f_{RPF}$, $4f_{RPF}$, $2f_{SPF}$ are analysed, and the predominant components of the inlet and outlet in pressure spectra locate at $2f_{RPF}$. Further, the non-uniform inflow leads to the offset of the X radial force and the Y radial force, which leads to the increasing of the asymmetric degrees of radial force. The non-uniform inflow increases the radial force at low frequency. In a word, it is expected that the present work provides a different view of designing pumps with the consideration of non-uniform inflow. It is very important to accurately evaluate the hydrodynamic characteristics with non-uniform inflow because of the safety of the nuclear reactor. In further study, experimental investigation on the pressure pulsations of the reactor coolant pump with channel head and straight pipe will be conducted and flow field of the inlet will be measured by PIV as well.

1. Introduction

The reactor coolant pump is one of the most important equipment in nuclear power plant. Reactor coolant pump is between the reactor and the steam generator, and is mainly used to force the coolant circulate in the primary circuit. Due to rotor–stator interaction, unsteady pressure pulsation has a direct impact on the stable and safe operation of pumps (Brennen). The pressure pulsations of the pump, as a boundary condition of reactor system, are usually the significant scientific issues.

In the advanced pressurized water reactor (APWR) reactor 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. The pumps are identical designs and are designed based on performance under uniform inflow with the straight pipe, but actually non-uniform suction flow is induced in the discharge pipe of the steam generator due to the complex geometry in the channel head, which might influence the

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Nomenclature

D_2	Impeller outlet diameter, 271.5 mm	f_R	Rotating frequency of impeller, 24.7 Hz
b_2	Impeller outlet width, 83 mm	f_{RPF}	Rotor passing frequency, 123.3 Hz
n_d	Rotating speed, 1480 r/min	f_{SPF}	Stator passing frequency, 271.3 Hz
ω	Angular velocity, 155 rad/s	u_2	Tangential velocity of impeller outlet, 21.03 m/s
η	Efficiency	Z_1	Impeller blade number, 5
D_1	Inlet pipe diameter, 300 mm	Z_2	Diffuser blade number, 11
p	Pressure, Pa	Φ_d	Nominal flow rate coefficient, $Q_d/(\omega D_2^2 b_2)$
C_p	Pressure coefficient, $p/(0.5\rho u_2^2)$	Ψ_d	Nominal head coefficient, $gH_d/(\omega^2 D_2^2)$
ρ	Water density, 1000 kg/m^3	n_s	Specific speed, $n_s = 3.65ndQ_d^{0.5}/H_d^{0.75}$, 387.5

performance of the pumps (Cheng et al., 2014). Furthermore, an effective approach should be developed to research pressure pulsation of the pumps with uniform and non-uniform inflow, which is sorely necessitated.

Up to now, only few researchers have studied the effect of the non-uniform inflow on the performance of pumps. Van Esch (2009) investigated the performance of a mixed-flow pump and hydrodynamic forces on the impeller under non-uniform suction flow with experimental method, they found that the performance of the pump is influenced by the type of suction velocity profile and a considerable steady radial force appeared when the suction flow is non-uniform. Xu et al. (2005) used 2-D PIV method to study the flow patterns of non-uniform flows in a rectangular open suction passage. Huang et al. (2002) investigated the flow characteristics within connection between steam generator channel head and pump suction by experimental method and found that the axial vortex is eliminated and axial velocity is uniform in the outlet section of the nozzle of the channel head. But the interaction between the channel head and the pump has not been investigated since no pumps are connected to the channel head in the test loop. And then, Cheng et al. (2014) investigate the effect of the velocity distortion generated by the steam generator on the performance of the two pumps by CFD method, and the results suggest that the nozzle dam brackets should be installed in the outlet pipe of the steam generator.

Generally, unsteady pressure pulsation excites mechanical vibrations of the pump even at the design operating condition. Up to now, lots of investigations have been carried out to study the unsteady flow, and the fast Fourier transform (FFT) method has been proved to be the most effective tool to analyse pressure fluctuations characteristics. Yao et al. (2011) analysed both frequency domain and time-frequency domain in a double suction centrifugal pump based on FFT and time-frequency representation methods. Parrondo-Gayo et al. (2002) also investigated the unsteady pressure distribution in a conventional centrifugal pump, and they paid more attention on pressure pulsations at blade passage frequency. Some studies focus on the influence of geometry on pressure pulsation by either experimental or numerical method. Spence and Amaral-Teixeira (2009) explored the effects of pressure pulsation. In their work, they took the form of a parametric study covering four geometric parameters by numerical analysis. And a rationalisation process aimed at reducing vibration through reductions in pressure pulsations has produced geometric recommendations. Yang et al. (2012, 2014) investigated unsteady pressure fields of the pump as turbine by numerical methods and illustrated that increasing blade tip clearance serves as an effective measure for reducing pressure pulsation. Benra (2006) investigated the periodic unsteady flow in a single-blade pump by CFD simulation and particle image velocimetry measurement method, and the results show that transient numerical simulations compare very well to velocity measurements. Pei et al. (2012, 2013) conducted the numerical investigation on the periodically unsteady flow of a single-blade pump and predicted the flow in a whole passage.

Under off-design conditions, some unexpected flow phenomena superposed to the rotor-stator interaction have considerable effect on vibration and safety. Toussaint et al. (Toussaint, 2006) conducted experimental investigation on the unsteady flow in the pump in off-design conditions and concluded that the pressure fluctuations occur at blade passing frequency, rotation frequency, and their harmonics. Barrio et al. (2008, 2010) presented a study on the fluid-dynamic pulsations and the dynamic forces in a centrifugal pump with different radial gap between the impeller and the volute. They estimated the dynamic radial forces and torque at blade passing frequency, whereas the progressive reduction of

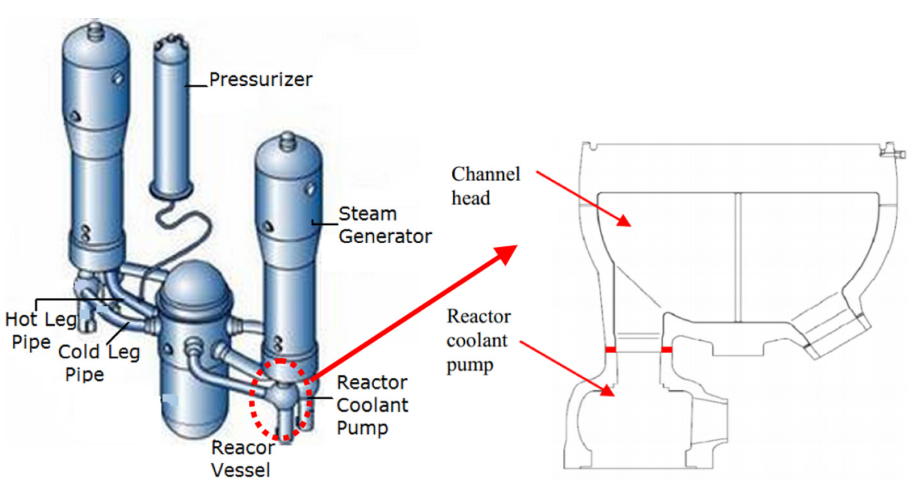

Fig. 1. Schematic diagram of connection type.