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Investigation on transient behavior of residual heat removal pumps in 1000 MW nuclear power plant using a 1D-3D coupling methodology during start-up period

Banglun Zhou, Jianping Yuan *, Jiaxing Lu, Feng Hong

National Research Center of Pumps, Jiangsu University, Zhenjiang 212013, China

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ABSTRACT

Residual heat removal pumps (RHRPs) are the key equipment in nuclear power plants, and their transient performances can sensitively affect the stability and reliability of pump system. A 1D-3D coupling methodology has been developed to investigate the instantaneous flow characteristics of the pump system during start-up period. In this methodology, the flow in the RHRPs was considered to be three-dimensional (3D) flow and the flow in pipe system was simplified to be one-dimensional (1D) flow. Due to the influence of the impeller structure displacement was taken into account, the SST k-ω turbulence model was selected to calculate the 3D flow field in the RHRPs. At the same time, the structure response caused by the flow loads was also obtained by using Fluid-structure interaction method. The 1D flow in the pipe system was calculated by Euler equations. The boundary condition at the shared interface was properly updated by the code MpCCI which was used to exchange the information between the two domains. Meanwhile, the head of the RHRP, the stress of impeller structure and the displacement of impeller were also obtained. The results show that the transient head is distinctly impacted during the startup period. Additionally, the stress of impeller structure rapidly increases with the increase of the rotating speed, and then the impact effect is found. These imply that instability phenomenon occurring during the startup process. Furthermore, the total displacement of impeller is increasing and its distribution is asymmetrical along the impeller radial. Finally, the maximum displacement occurs at the impeller hub where which is near the rim between two blades, due to the centrifugal force at the rim is larger than that in other regions and the relative low impeller rigidity.

1. Introduction

RHRPs used in Radiation Research Association are components, which are critical to nuclear plant operations. One of their main functions is discharge heat in the reactor coolant system under normal shutdown condition in nuclear power plant. And the other function is that pumping low pressure water from Spent Fule Pool Cooling System to the reactor coolant system when automatic depressurization system finished start-up. In some situations, they are used to remove the residual heat in tank replacement in containment.

RHRPs circulate coolant through residual heat removal (RRA) system which includes heat exchangers and the reactor vessel when reactor coolant pumps are not operating to maintain the plant at cold shutdown condition. RHRPs have to start 20 times at least every year. They as a special purpose pumps are strict requirements in all aspects of their reliability, stability, safety and performance. The reliability of the pump system is mainly determined by unsteady operation of pumps. The rapid start of pumps is always accompanied with large pressure fluctuation and big impact on head, which can cause the equipment and pipe system failure, so that the system cannot operate normally. Therefore, the pumps' start reliability determines the reliability of the pump system to a great extent. Rotating speed, flow, head and loads change rapidly in the pumps quick start process which shows special nature different from the steady start process have a notable effect on the system safety. Therefore, study on transient characteristics of RHRPs by comparing the differences of the internal characteristics between in the steady state and in start-up period, have important significance on both theory and practice, and provide guidance for the pump hydraulic model optimization.

In the application of nuclear engineering, transient behavior of the feedwater pump trip in start-up for Lungmen Plant was pre-

* Corresponding author.
E-mail address: yh@ujs.edu.cn (J. Yuan).

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Nomenclature

H	head, m	b_2	the wide of impeller outlet, mm
P	shaft power, kW	u_2	the impeller tip speed, m/s
Q	flow rate, m^3/h	σ_{eq}	equivalent stress, MPa
Z	the number of impeller blades	t	time, s
Z_d	the number of guide vane blades	E	Young's modulus, GPa
n	impeller rotating speed, r/min	ν	Poisson's ratio
D_j	inlet diameter of impeller, mm	ρ	density, kg/m^3
D_2	outlet diameter of impeller, mm		
D_4	outlet diameter of diffuser, mm		

dicted (Ma et al., 2011). The transient flow in pump considering the effect on pump failure was studied (Rohani and Afshar, 2010). The flow characteristics in the impeller of a nuclear centrifugal pump were studied under transient conditions (Fu et al., 2016). For the normal pumps application, methods for startup performance of centrifugal pumps are mainly theoretical analysis, numerical and experimental research (El-Sadi and Esmail, 2006; Hu et al., 2012; Jiang et al., 2011; Huang et al., 2016). The transient behavior of the pump during start-up period in Tehran Research Reactor was investigated by some researchers (Farhadi et al., 2007; Farhadi, 2011) using a mathematical model based on a working practical approximation. The results show fair agreement between the prediction of the model and the experimental data of pump characteristic. The transient performance of reactor coolant pump was studied based on the momentum conservation equation of the primary coolant and the moment balance relation of the reactor coolant pump in primary coolant system during start-up period (Gao et al., 2013). The transient pump total head, the acceleration head, the overcoming friction head and the transient torques during a pump startup are obtained in this work. The analytical non-dimensional flow rate, the pump speed, heads and torques are all affected by an energy ratio. Thanapandi studied the transient characteristics of a centrifugal pump during starting and stopping periods (Thanapandi and Prasad, 1995). The results show that the pump dynamic characteristics based on a purely unsteady analysis display considerable departure from their steady-state characteristics. Li et al. investigated transient characteristics and flows of a centrifugal pump during its startup period and transient flow evolutions in the pump's diffuser are observed using PIV (Li et al., 2011). In the early stage of the startup, the transient head coefficient is lower than the steady state value and the main reason caused this phenomenon is the transient vortex evolution between blades. In later stages, the specific performance gradually comes back to the steady value due to the intensity of the spatial vortex evident on hub declines and the main flow stream reinforces. Yuliang Zhang et al. studied the transient behavior of a prototype centrifugal pump with an open impeller during rapid starting period (Zhang et al., 2013). The quasi-steady analysis is incompetent to exactly evaluate the transient flow during startup period compared the non-dimensional results. Sami Elaoud et al. predicted the instantaneous behavior of the flow under the pump start-up transient conditions (Elaoud and Hadj-Taïeb, 2011). The results show that the evolution of the hydraulic variables is well influenced by the pump starting time. Li et al. studied the transient flow in a centrifugal pump during rapid starting period by developed a physical model composed of a pipe system and pump (Li et al., 2010).

In many mechanical engineering applications, FSI was considered as a useful calculation approach to address multi-physics problems. For example, the behavior of the transient dynamic on the rotor structure which induced by the flow field loads in a centrifugal pump is investigated by a two-way coupling method (Yuan et al., 2011). Noise in multi-stage centrifugal pumps was studied base on a one-way coupling method by Kato et al. (2005). The noise in a centrifugal pump induced by the flow was predicted by FSI (Langthjem and Olhoff, 2004). The characteristic of transient flow affected by the motions of structure in a single-blade sewage centrifugal pump was investigated based on the two-way coupling method (Pei et al., 2013). The dynamic stress of impeller induced by fluid loads was calculated by using two-way coupling method in a sewage centrifugal pump (Pei et al., 2014).

In the present work, two RHRPs were installed in RRA system. The coolant circulate between the RRA heat exchangers and the reactor vessel is to maintain the plant in cold during shutdown process when reactor coolant pumps are not operate. The startup of RHRP was investigated by a 1D-3D coupling methodology which is combined with Flowmaster code and CFX code. The RRA system mode for the RHRP startup process simulation was built in software Flowmaster and the flow in this system was simplified to be one-dimensional flow. The three-dimensional flow in RHRP was calculated by using CFX considering FSI. A multi physical coupling tool MpCCI was used to transfer 1D-3D coupled flow information between one-dimensional flow in Flowmaster and three-dimensional flow in CFX. The 1D-3D coupling methodology can improve the simulation accuracy, due to systems and fluid components can achieve fluid flow parameters iteration at the import and export of a single fluid component and three-dimensional flow field analysis consider the impact on the performance of the whole system. As for the flow in RHRPs, SST k-ω turbulence model was selected to calculate. The structure response of impeller was first established by using strong two-way coupling FSI. The dynamic stresses of impeller and the displacement on impeller were studied in detail.

2. 1D-3D coupling methodology

2.1. 1D-3D coupling procedure

In order to accurately obtain the pump instantaneous performance by taking the influences of the other components of the pump system in the startup into account, a 1D-3D coupling methodology has been developed to predict the flow in the whole pump system. The flow in pump is regarded as three-dimensional flow to address the unsteady flow phenomenon. The flow in the pipe system are assumed to one-dimensional flow to calculate transmission of the flow. One of the advantage of the coupling methodology is that it takes less computing resources than the whole three-dimensional flow calculation in the pump system. The flow at the pump outlet provides the source for the flow movement of the pipe system. At the same time, the pump instantaneous performance can be affected by the behavior of the pipe system. The 3D flow inside the pump is calculated by a commercial