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Investigation on transient flow of a centrifugal charging pump in the process of high pressure safety injection

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HIGHLIGHTS

- The transient flow characteristics of the charging pump with the first stage impeller in the HPSI process have been investigated numerically by CFD.
- The hydraulic performance of the charging pump during the HPSI are discussed, andthe absolute errors between the simulated and measured results are analyzed in the paper.
- Pressure fluctuation in the impeller and flow pattern in the impeller were studied in the HPSI process. It is influenced little at the beginning of the HPSI process while fluctuates strongly in the end of the HPSI process.

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ABSTRACT

In order to investigate the transient flow characteristics of the centrifugal charging pump during the transient transition process of high pressure safety injection (HPSI) from $Q = 148\,m^3/h$ to $Q = 160\,m^3/h$, numerical simulation and experiment are implemented in this study. The transient flow rate, which is the most important factor, is obtained from the experiment and works as the boundary condition to accurately accomplish the numerical simulation in the transient process. Internal characteristics under the variable operating conditions are analyzed through the transient simulation. The results shows that the absolute error between the simulated and measured heads is less than 2.26% and the absolute error between the simulated and measured efficiency is less than 2.04%. Pressure fluctuation in the impeller is less influenced by variable flow rate in the HPSI process, while flow pattern in the impeller is getting better and better with the flow rate increasing. As flow rate increases, fluid blocks on the tongue of the volute and it strikes in this area at large flow rate. Correspondingly, the pressure fluctuation is intense and vortex occurs gradually during this period, which obviously lowers the efficiency of the pump. The contents of the current work can provide references for the design optimization and fluid control of the pump used in the transient process of variable operating conditions.

1. Introduction

The centrifugal charging pump is an important component in the reactor coolant system of nuclear power plants, and the reliability of the charging pump is directly related to the safely operating of the nuclear power plant. It is required that the charging pump need to operate under high pressure injection conditions in case the reactor coolant system of the nuclear power system is broken. Transient characteristics, such as vortexes, reverse flow and pressure fluctuation occur in the pump in the transient process of variable operating conditions. The flow during this period will not only affect the hydraulic performances of the charging pump, but also endanger the operation of the nuclear power plant. So it attaches great importance to investigate the transient characteristics of the charging pump in the process of high pressure safety injection (HPSI).

Many researches on charging pump have been done in recent years. Pearson (1997) introduced the structures of charging pumps and provided the maintenance guides to charging pumps. Yuan et al. (2010) put forward a multi-operating-condition hydraulic design method for centrifugal charging pumps, and the hydraulic performances meet the requirements of the nuclear power plant. Wu et al. (2010) used an experimental system to measure the external and internal transient characteristics under different flow-rates. In addition, Zhu et al. (2013) and Zhang et al. (2014) investigated the transient flow patterns of the charging pump in the process of

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Nomenclature

D_1	inlet diameter of impeller (mm)
D_2	outlet diameter of impeller (mm)
b_2	outlet width of impeller (mm)
φ	wrap angle (deg)
H	head (m)
Z	number of blades
r	radius of impeller (mm)
n	rotation speed (r/min)
Q	flow rate (m^3/h)
v	velocity (m/s)
t	time (s)
P	pressure (Pa)
M	torque (N m)

Subscripts

1	inlet
2	outlet
a	actual model
b	test model

variable operating conditions and the pressure characteristics of the same pump model also was discussed in Zhang et al. (2015). Fu et al. (2012a,b, 2013a,b, 2014) has done many researches on anti-seismic calculation, torsional vibration characteristics, cavitation characteristics, the critical rotating speed calculation and variable operating features of charging pumps.

However, there was almost no research concerning the transient characteristics in the process of variable operating conditions at large flow rate. So it's extra-urgent to investigate the transient characteristics in this process.

Nowadays, with the development of CFD technology, numerical simulation has been greatly developed and widely used in the transient flow calculation. CFD technology has been successfully used in the transient flow investigation of pumps during the starting and stopping periods (Li et al., 2010; Wu et al., 2011; Liu et al., 2011). In this paper, both experimental and numerical methods were used to investigate the transient characteristics in the HPSI process from $Q = 148\ m^3/h$ to $Q = 160\ m^3/h$ of a charging pump. The transient flow characteristics on the pump are investigated and the research results can be used as reference for future studies and applications.

2. Experiment

2.1. Pump model

The first stage of the charging pump is selected to investigate the transient flow characteristics in the HPSI process. The 3D geometry structure, which used in the simulation, includes the inlet section, impeller and double channels volute, as shown in Fig. 1. The pump is designed to rotate at $n = 4500$ rpm and the specifications of the geometry are given in Table 1.

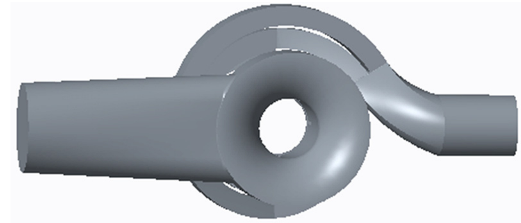

Fig. 1. 3D model.

Table 2
Test precision standard of grade 2 in China (Guan, 2011).

Contents	Q	H	P	η
Uncertainty	≤±2.0%	≤±1.5%	≤±1.5%	≤±2.8%

2.2. Test rig

The test is carried out in Jiangsu University according to national grade 2 precision of China. The precision standard of grade 2 is given in Table 2 and the test rig is shown in Fig. 2. The pump rotates at the speed of $n = 2900$ rpm in the test. According to formula (1)–(3) (Guan, 2011), the similarity laws are applied to present the corresponding flow rate at $n = 4500$ rpm in each operating point.

$$\frac{Q_a}{Q_b} = \frac{n_a}{n_b} \tag{1}$$

$$\frac{H_a}{H_b} = \left(\frac{n_a}{n_b}\right)^2 \tag{2}$$

$$\eta_a = \frac{\eta_b \times 100\%}{\eta_b + (100 - \eta_b)\left(n_b/n_a\right)^{0.17}} \tag{3}$$

The discharge valve is adjusted step by step according the flow rate increasing from 148 m^3/h to 160 m^3/h, which is the high pressure safety injection process. When the pump operated at $Q = 148\ m^3/h$ stably, the discharge valve was adjusted with a uniform rate to increase the flow rate and it would be stopped until the flow rate increased to 160 m^3/h approximately. The variable flow rate during the adjustment process was measured by the LWGY-200A turbine flow meter with 0.5% measurement uncertainty. The pressure in the inlet and outlet was measured by pressure sensors, whose uncertainty is 0.1%. All flow passages, water tank and the pump are filled with water 25 °C with density $\rho = 1000\ m^3/h$ and dynamic viscosity $\mu = 0.001$ Pa s.

The Q–t curve of volume flow rate variation is obtained from test data from 148 m^3/h to 160 m^3/h is shown in Fig. 3. Flow rate is increased quickly before 1.2 s and then it is increased slowly till the end of the HPSI process. The image of the flow rate variation is depicted by formula (4), which is the most important in the transient simulation and inserted as outlet boundary condition.

$$Q = -2.0555t^2 + 12.414t + 147.78 \tag{4}$$

Table 1
Specifications of the pump model.

Geometric specifications			Hydraulic specifications		
Inlet diameter (mm)	D_1	140	Nominal speed (rpm)	n	4500
Outlet diameter (mm)	D_2	230	Nominal flow rate (m^3/h)	Q_d	110
Outlet width (mm)	b_2	16	Nominal head (m)	H_d	135
Wrap angle (deg)	φ	140			
Blade number	Z	3			