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Transient flow analysis of integrated valve opening process

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HIGHLIGHTS

- The control rod hydraulic driving system (CRHDS) is a new type of built-in control rod drive technology and the integrated valve (IV) is the key control component.
- The transient flow experiment induced by IV is conducted and the test results are analyzed to get its working mechanism.
- The theoretical model of IV opening process is established and applied to get the changing rule of the transient flow characteristic parameters.

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ABSTRACT

The control rod hydraulic driving system (CRHDS) is a new type of built-in control rod drive technology and the IV is the key control component. The working principle of integrated valve (IV) is analyzed and the IV hydraulic experiment is conducted. There is transient flow phenomenon in the valve opening process. The theoretical model of IV opening process is established by the loop system control equations and boundary conditions. The valve opening boundary condition equation is established based on the IV three dimensional flow field analysis results and the dynamic analysis of the valve core movement. The model calculation results are in good agreement with the experimental results. On this basis, the model is used to analyze the transient flow under high temperature condition. The peak pressure head is consistent with the one under room temperature and the pressure fluctuation period is longer than the one under room temperature. Furthermore, the changing rule of pressure transients with the fluid and loop structure parameters is analyzed. The peak pressure increases with the flow rate and the peak pressure decreases with the increase of the valve opening time. The pressure fluctuation period increases with the loop pipe length and the fluctuation amplitude remains largely unchanged under different equilibrium pressure conditions. The research results lay the base for the vibration reduction analysis of the CRHDS.

1. Introduction

The control rod is the major reactivity control equipment of the nuclear reactor. It performs the reactor startup, shutdown and different power operation functions through moving up and down, scram and holding position in the reactor core respectively. Normally the control rod is driven by the driving mechanism. Based on the in-depth research of the hydraulic control rod driving system (HCRDS) (He and Han, 2009) of the 5 MW low temperature nuclear heating reactor which is invented by INET, Tsinghua University, and combined with the advantages of magnetic jack in pressurized water reactor (PWR), the control rod hydraulic driving system (CRHDS) is developed as a new type of built-in control rod drive technology (Bo et al., 2005). The CRHDS is shown in Fig. 1 which is composed of circulating pump, filter, integrated valve and control rod hydraulic drive mechanism (CRHDM). The reactor coolant is used as the working medium of the CRHDS. The water in the reactor pressure vessel is pressurized by the pump and then flows into the IV through the filter. The pulse water enters into the CRHDM controlled by the IV so as to achieve the reactor control rod step-up, step-down and scram functions. The design of the CRHDS doesn't penetrate the pressure vessel, shortens the control rod drive line, and eliminates the uncontrolled rod ejection accident. The CRHDS is driven by hydrostatic pressure and can position the control rod more accurately. This technology can be directly applied to the integrated nuclear reactor.

Acronyms: CRHDS, control rod hydraulic driving system; IV, integrated valve; HCRDS, hydraulic control rod driving system; PWR, pressurized water reactor; CRHDM, control rod hydraulic drive mechanism.

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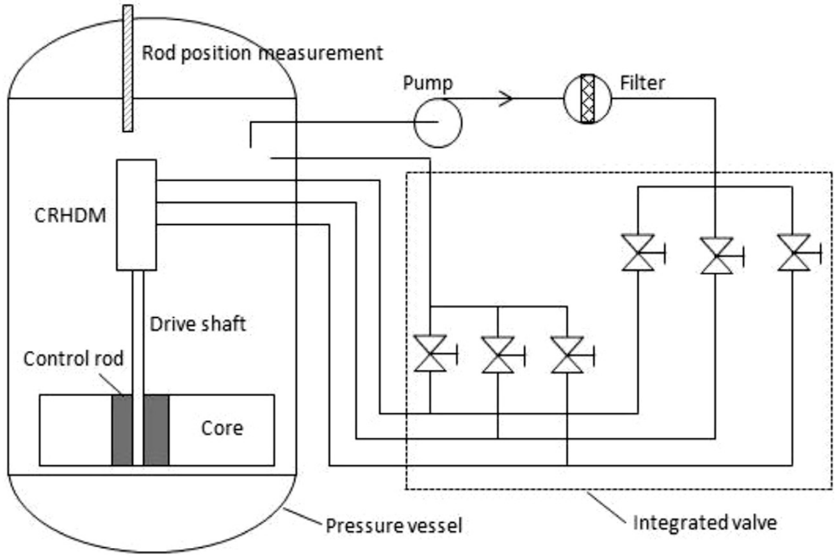

Fig. 1. Schematic diagram of CRHDS.

The IV is a direct action solenoid valve which moves quickly. There are obvious transient flow phenomenon in the hydraulic drive loop because of the fast closing and opening of the IV in the CRHDS working process (Wylie and Streeter, 1983; Zhang et al., 1994). Coupled with the actions of the hydraulic cylinder of the CRHDM, this transient flow process results in high pressure fluctuation in the system loop (Otwell, 1984; Ghidaoui, 2005). The pressure fluctuation process brings about vibrations and noise to the loop pipe and equipment. It also interferes with the normal operation of the measuring instruments and does harm to the long-term reliable operation of the loop circulation pump. Therefore, it is necessary to analyze the transient flow in the drive system caused by the IV operation. The study lays the base for the vibration analysis of the drive loop and the development of the pressure pulsation attenuator (Zhang and Zhou, 2011).

As for the IV, Cai wei has studied the steady flow resistance of the IV inner flow channels when the IV is fully open and closed through theoretical and experimental methods. The IV steady flow resistance coefficient was obtained (Cai et al., 2007, 2008; Qin et al., 2010). The electromagnetic force test was carried out for the solenoid valve under different working conditions. The variation laws of the electromagnetic force with the valve design parameters and the electromagnetic coil drive currents were obtained (Liu et al., 2011). The IV dynamic opening process is analyzed in this paper. The working principle of the IV is introduced. The IV transient flow experiment was carried out and the transient flow mechanism in the IV opening process is analyzed based on the experiment. The transient flow model of the test loop during the IV opening process is established which includes the system control volume equations and the boundary condition equations. The model calculation results agree well with the experiment results. Based on the validated model, the variation of characteristic parameters in the IV opening process at high temperature are analyzed. The research results lay the base for the vibration reduction analysis of the CRHDS.

2. IV working principle

The IV is composed of lift valve, transfer valve and gripper valve which are separately connected with the corresponding hydraulic cylinders of the CRHDM through stainless steel tubes. The structure and working principles of the three valves are similar and the lift valve will be analyzed as an example. The lift valve consists of solenoid valve and flow channels. Structure of solenoid valve and valve core flow channel is shown in Fig. 2. The solenoid valve contains moveable iron core, electromagnetic coil, push rod and static iron core, and the first three of which are the valve head electromagnetic drive unit. The valve core flow channel contains the top piston, core stem and bottom piston. The movable iron core is connected with the top piston via the push rod. The top piston is connected with the bottom piston via the core stem.

Structure of the IV flow channel is shown in Fig. 3. The flow channel consists of in-rod flow channel and out-rod flow channel. The in-rod flow channel is highlighted in Fig. 3(a) and its flow direction is 1-2-3-4-5-6-7. The out-rod flow channel is highlighted in Fig. 3(b) and its flow direction is 1-2-3-4-5-8-9-10-11. The bottom water cavity, valve core vertical channel and top water cavity form the valve core flow channel which is shown at the bottom of Fig. 2. The structure of valve core flow space changes quickly in the IV opening process which is the focus of the transient flow boundary condition analysis.

The water flows into the high pressure water cavity and then into bottom water cavity through the sidewall flow channel. The valve is a normally closed electromagnetic valve. Initially, the solenoid valve is powered off and the transmission part of the valve head electromagnetic drive unit is at the top. The bottom piston has a close contact with the upper annulus wall of bottom water cavity under the reset spring force which is shown in Fig. 2.

When the solenoid valve is energized, the piston would move down due to the electromagnetic force. The bottom piston separates from the upper annulus wall of the bottom water cavity and the water flows into the valve core vertical channel. The main flow gets split into two streams. One part flows into the lateral flow channel and then gets out of the valve. The other part flows into the top water cavity and converging water chamber successively, and then flows out of the valve at last. The distance between the top piston and the lower annulus wall of top water cavity becomes smaller and smaller in the IV opening process. The flow rate of in-rod flow channel increases while the flow rate of the out-rod flow channel decreases. The top piston contacts the lower annulus wall of top water cavity when the IV opening process is over. Meanwhile, the in-rod flow channel is completely open and the out-rod flow channel is fully closed. Therefore, the out-rod flow channel undergoes a close-open-close process whose flow rate firstly increases to peak and then decreases to zero.