Development of a body force model for a marine reactor in heaving motion

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Abstract. In the marine environment, sea wave affects the reactor coolant periodically through the additional forces. In this paper, a modified mathematical model is proposed and applied in the RELAP5/3.2 code in order to simulate the marine heaving condition. Then the influence mechanism of heaving motion and natural circulation features for an integral natural circulation reactor are analysed and discussed. The results show that the original flow distribution of prototype reactor is broken, however, the natural circulation is not interrupted. What’s more, the calculation shows that large amplitude and long period of heaving motion bring out violent oscillation, which is referential to the safety analysis of the reactor core.

1. Introduction

In recent years, the research of a small reactor has been implemented in China. Different from the traditional reactor, the integral and self-pressurization design of primary system are adopted for the small research reactor. It is important that the reactor operates under full power natural circulation condition by eliminating the primary coolant pump. Primary coolant of the research reactor relies on the density difference between the reactor core and main heat exchanger to produce the drive head. Many advanced passive safety concepts such as passive residual heat removal system (PRHRS) and passive safety injection system (PSIS) have also been equipped for the reactor. The special designs which improve the reactor safety performance have been verified with many integral effect tests on the land. However, the natural circulation characteristic of the reactor influenced by marine motions need to be studied for the application in the marine environment.

In the marine environment, sea wave affects the reactor coolant periodically through the additional forces, resulting in changes of mass, momentum and heat transfer characteristics. According to the direction of wave motion, the marine motions generally consist of many conditions, such as rolling, pitching and heaving, as shown in Figure 1. In the recent years, a series of studies have been implemented on marine condition. Many scholars tried the explanation for the mechanism of the marine motion. Pang et al. [1] established a mathematical model of coolant for marine motion with the basic flow equations and the influence of marine motions. Gao et al. [2] explained the impact mechanism of heaving motion, however, the study ignored the effect of gravity drop and the extrapolation of the method is limited. Some scholar combined the mathematical model to the commercial codes with relatively simple verification. Wang et al. [3] studied the phase lag relationships between the pressure drop and flow rate in a circular coolant tube. Qian et al. [4] considered ocean conditions of vertical coolant channel by adding the additional forces to the
momentum equations. Tan et al. [5] developed a system analysis code suitable for ocean conditions, modifying the momentum equations simply. However, the more verification in the complicated coolant system needs to be explained. Based on the flow and heat transfer models of laminar flow and turbulent flow in horizontal and vertical channels, Yan et al. [6] explored a thermal-hydraulic code and simulated the operation of a passive residual heat removal system in marine motion successfully. Experimental and theoretical research on single-phase rolling loop were carried out by Gong et al. [7]. The results indicated that the natural circulation flow was not formed under cold state. Xia et al. [8] studied the rolling features of a conceptual reactor, showing that thermal-hydraulic symmetry of the reactor was changed. Feng et al. [9] established a code to explore the influence of heaving motion based on the experimental loop. Du et al. [10] studied the marine motion to the single-phase forced circulation with the theoretical governing equations and CFD simulations. The changes of flow configuration and frictional drag are explained reasonably. What’s more, Du studied the heat transfer characteristics of a circular channel under marine conditions experimentally. The CFD predictions are matched with the experimental data successfully [11]. Their results are referential, however, marine motion effects of specific reactor still need to be investigated.

Previous research [12] has shown that the influence of inclination can be ignored to some degree and the most influential motions include heaving, rolling, etc. Thus, the paper focuses on the analysis of the integral reactor under heaving condition. Flow features of heaving motion are analyzed by using the modified mathematical model, which is suitable for the simulation of heaving motions.

**Figure 1.** Diagram of typical motions in marine environment.

### 2. Mathematical model

#### 2.1. Body force model

The additional forces of fluid particle under marine conditions are described with a mathematical model of body force. Compared with the inertial coordinate system, the in translational motion belongs to a non-inertial coordinate system. The coordinates of fluid particle in the non-inertial coordinate system can be expressed as:

\[ \vec{r} = x\hat{i} + y\hat{j} + z\hat{k} \]  \hspace{1cm} (1)

For fluid particle in the channel, the momentum equation can be expressed as:

\[ \rho \frac{Du}{Dt} = -\frac{\partial p}{\partial l} + \rho \vec{f} \cdot \hat{I}_0 \]  \hspace{1cm} (2)

The additional force in Equation (2) can be expressed as:
\[
\bar{f} = \bar{f}_g - a_n - \bar{\beta} \times \bar{r} - \vec{\omega} \times (\vec{\omega} \times \bar{r}) - 2\vec{\omega} \times \bar{V}
\]  

(3)

where \(\vec{\omega}\) and \(\bar{\beta}\) are rotating angular velocity and angular acceleration, respectively. \(\bar{\beta} \times \bar{r}\), \(\vec{\omega} \times (\vec{\omega} \times \bar{r})\) and \(\vec{\omega} \times \bar{V}\) are tangential force, centrifugal force and coriolis force, respectively [13]. For the one-dimensional flow, coriolis force is always ignored because the direction of force is perpendicular to the flow direction.

The \(\bar{f}_g\) in Equation (3) is the effective gravity can be expressed as:

\[
\bar{f}_g = -g \bar{k}
\]

(4)

Suppose that a flow channel in the non-inertial coordinate system has the point A and point B. The body force terms in one-dimensional momentum equations of heaving motion can be expressed as:

\[
\rho \bar{f} \cdot \bar{i}_0 = -\rho g \left[ a_0(t) \right] \left( \frac{z_a - z_b}{L} \right)
\]

(5)

Translational acceleration \(a_0^n\) and angular velocity \(\omega^n\) can be expressed as:

\[
a_0^n = \omega^\pi \frac{2\pi T}{T_p} \sin \left( \frac{2\pi t}{T_p} \right)
\]

(6)

\[
\omega^n = \frac{2\pi \omega^\pi}{T_p} \cos \left( \frac{2\pi t}{T_p} \right)
\]

(7)

where \(\omega^\pi\) is the motion amplitude, \(T_p\) represents the motion period.

The modified model is implemented into subroutines of RELAP5 code in order to calculate the momentum equations.

2.2. Modelling of the system

Modelling of the reactor system is the basis for analyzing the characteristics of marine motions. In this paper, the REALP5 code is selected in the modelling for the powerful built-in functions and support for simulation of the thermal-hydraulics components. A diagram of the research reactor nodalization is shown in Figure 2. In the nodalization, most of the major components are considered.

The primary coolant system and middle loop system are simulated closely to reality as far as possible. Coolant channels of the core consist of average channel, hot channel and bypass channel. Core power is calculated by point kinetic model with feedback input. Self-pressurized spaces of the RPV are divide into independent gas space, mixture space and independent water space. Top volumes of the self-pressurized space are connected with valve components to simulate the pressure protection system. Coolant channels of the main heat exchanger are divided into two parts to simulate the double-tube bundle structure. Main components of the middle loop system are also considered, including secondary side of the main heat exchanger, pressurizer, inlet plenum, U-tubes, out plenum, and circulating pump. As for secondary loop system, the feed water and steam outlet are simplified as boundary conditions. With the modelling, the full-power natural circulation in the coolant loops is successfully established, which can reflect the operating feature reasonably. Thus, the marine motion can be inducted to the established steady-state in the next steps.
3. Results and discussions

3.1. Natural circulation feature of heaving motion
The periodic heaving motion is introduced to the research reactor in the simulation based on the full-power operating condition. As mentioned previously for the body force model, the additional force caused by heaving motion is parallel to gravity. In fact, the eight heat exchanger branches in Figure 2 is arranged symmetrically around the reactor core. It is shown in Figure 3 that the flow characteristics of heat exchanger branches in heaving motion (0.5g&8s) are identical (only three branches characteristics are shown due to the symmetry). The results also show that the period of core flow is consistent with the heaving period. What’s more, calculation results show that the mathematical model established for heaving motion is effective.

For the natural circulation, the influence of heaving motion is mainly determined by the combined relationship of additional forces and density difference. Periodic additional forces bring out fluctuation of coolant flow rate and reactor power. As can be seen from Figure 4 and Figure 5, the oscillation amplitude of coolant flow rate is much larger than the reactor power. Therefore, the coolant temperature and density oscillate periodically.

The fluctuation of coolant temperature is small when the additional forces are weak, so the influence of density distribution remains unchanged. However, the actual influence is always superposed with the changes of density difference and additional forces, which affect the driving force of natural circulation jointly. Under the condition of 0.5g&8s, the fluctuation up and down of the core flow is about 76%. Corresponding fluctuation of core outlet temperature can also be obtained. The results show that due to the forced circulation of the middle loop, the cooling capacity of the middle loop is continuous and sufficient, so slight fluctuations of the core inlet temperature can be observed.
3.2. Influence of heaving amplitude and period on natural circulation

Heaving amplitude influences the motion according to the maximum value of the translational acceleration. The large heaving amplitude leads to obvious fluctuation of core flow and decrease of nature circulation ability. Figure 6 shows that the larger the heaving amplitudes, the greater impact on the natural circulation. Figure 7 shows that longer periods brings out more severe oscillation due to the longer impact time under the same amplitude. However, with the increasing of period, the impact tends to be smooth.
4. Conclusions

In this paper, a modified mathematical model is implemented into the RELAP5 code to simulate the heaving motion. Although some theoretical and simulation methods have been applied in some literatures, the study for the specific integral natural circulation reactor is not sufficient. In the present work, flow characteristics in marine heaving motion are investigated by using the modified RELAP5/3.2 code. From the analysis, the flow distribution is changed greatly due to the heaving motion, however, the natural circulation is not interrupted. The influence mechanisms for heaving motion are analyzed, which reflects that heaving amplitude and period are the most important factors to the flow. The work is beneficial for the further studies for the reactor application in the complicated marine conditions.

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