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Simulation investigation of ocean motion on small reactor based on modified system code

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Abstract. Offshore nuclear small reactor is a promising research direction during recent years. In order to carry out system simulation and safety analysis under accident conditions for marine reactors, the classic thermal-hydraulic system analysis code RELAP5 is modified by taking heaving, inclining and rolling motion into consideration in this paper. Additional forces are added to the momentum equation for heaving and rolling, and control volume coordination are transformed for inclining and rolling. Then, a simplified small reactor with two loops is simulated by the modified code and the effect of ocean motion is investigated. Generally, heaving leads to the periodic fluctuation of mass flow rate, inclining would cause the decrease of total mass flow through the core, and the effect of rolling is more complex. Simulation analysis is also performed on two design basis accident LOCA and LOFA in this study. Safety related conclusions are obtained about the impacts of various ocean motion.

1 Introduction

Nuclear energy has broad application prospects on marine power, exploitation of offshore resources and offshore power generation platform. Ocean conditions are complicated and changeable with storms or waves or other adverse climate, which have potential impacts on nuclear power plant equipment and thermal-hydraulic effects of coolant.

Although the movement of ships is complex, the typical marine conditions could be decomposed of heaving, inclination and rolling by neglecting small effect act. Researchers have done a number of work on the influence of ocean motion on general hydraulic thermal phenomena. Ishida I and Ishida T et al. analyze the operation characteristic of marine reactor DRX by RETRAN-02/GRAV which is improved to simulate the effect of ship motions [1,2]. Murata et al. performed a series of single-phase natural circulation tests to investigate effects of the rolling motion on its thermal-hydraulic behavior [3]. Tan et al. conducted experiments to investigate the instability of natural circulation under rolling motion [4]. Yan B H and He L et al. studied natural circulation characteristic of SMR based on modified RELAP5 code [5,6].

Although the basic theoretical model of ocean condition is achieved, the ocean impact on overall reactor and design basis accident are need to be discussed. As the modification of thermal hydraulic system code is an effective approach to analyze characteristics of small marine reactor under ocean conditions, in this paper, the widely used system code RELAP5 is modified by introducing additional forces into momentum and transforming coordinate of system to adapt the condition of heaving, inclining and rolling. Then the simplified model of small reactor is built, and simulation is performed under the normal operation and design basis accident conditions to study the effect of ocean motions.

2 System code modification

2.1 modification of momentum equation

In order to simulate the small reactor behavior under ocean environment, additional forces are added on the momentum equation of RELAP5 code. Coordinate and elevations are also converted for corresponding conditions.

Heaving and rolling motion introduce additional forces in the momentum equation, which in RELAP5 can be expressed as,

$$\alpha_k\rho_k A\frac{\partial v_k}{\partial t}+\frac{1}{2}\alpha_k\rho_k A\frac{\partial {v_k}^2}{\partial x}=-\alpha_k A\frac{\partial P}{\partial x}+F_{bk}+\Gamma_k A(v_{kI}-v_k)-F_{wk}-F_{ik}-F_{vk}+F_{heav}+F_{roll} \quad (1)$$

Where the subscript k indicates gas and liquid. The first term on the right side represents the pressure difference, F_{bk} is the volume force, the third term is the momentum exchange caused by the mass exchange, F_{wk} is wall friction, F_{ik} is the interfacial friction, F_{vk} represents the virtual mass force, and the added F_{heav} and F_{roll} is the additional forces generated by heaving and rolling separately and can be indicated as $\alpha_k\rho_k A a_{heav/roll}$.

Studies show that the complex ship motion can be approximately equal to the superposition of single

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sinusoidal motion with given amplitude and period. The additional acceleration of heaving is shown as,

$$a_{heav} = -\frac{4\pi^2 x_h}{T_h^2} sin\,(\frac{2\pi t}{T_h}) \quad (2)$$

where x_h is the amplitude and T_h is the period of simplified heaving process.

As for rolling, based on previous work, the additional acceleration is introduced by the summary of tangential acceleration a_t and centripetal acceleration a_c,

$$a_{roll} = a_t + a_c = \beta_{roll} \times \mathbf{r} + \omega_{roll} \times (\omega_{roll} \times \mathbf{r}) \quad (3)$$

Where $\mathbf{r}$ is the position vector of each control volume, ω_{roll} is the angular velocity of rolling, β_{roll} is the angular acceleration of rolling. ω_{roll} and β_{roll} can be calculated through the given rolling amplitude θ_a and period T_r as,

$$\omega_{roll} = \frac{2\pi\theta_a}{T_r}\cos\frac{2\pi t}{T_r} \quad (4)$$

$$\beta_{roll} = -\frac{4\pi^2\theta_a}{T_r^2}\sin\frac{2\pi t}{T_r} \quad (5)$$

$\mathbf{r}$ defined as (x, y, z) can be determined based on the unit vector of rolling axle $\mathbf{e} = (e_x, e_y, e_z)$.

2.2 modification of coordinate and elevation

Inclining and rolling motion will change the geometry coordinate of the reactor system so as to affect the hydraulic characteristics of reactor. As for natural circulation condition, the inclining of system may lead to a transformation from horizontal part to vertical part which will change the height difference between the heat and cold source.

The transformed coordinate(x', y', z') of each control volume in the system can be determined according to the unit vector of rolling axle $\mathbf{e}$ and inclination angle θ_0 at the current time as computed in equation 6. Besides, the relative coordinate of each control volume to the rolling axle should also be recorded to calculate the moment of rolling force.

Limited by the completeness of relevant parameters of experiment in the open literature, the modified system code is only verified by comparing the trend of calculation results to similar systems.

3 Simulation of small reactor under ocean motion

3.1 Modeling of a simplified small reactor

To investigate the effect of ocean motion on design basis accident such as LOCA and LOFA for small marine reactor, a simplified model as in Fig.1 is built by modified system code. Where pipe100 and adjacent heat structure presents for the reactor core, pipe 106, 403 and 206, 503 simulate the steam generators of two loops which remove heat from the core. Referenced from relevant literature, the main design parameters are listed in Table 1.

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} e_x^2(1-cos\,\theta_0)+cos\,\theta_0 & e_xe_y(1-cos\,\theta_0)-e_z\,sin\,\theta_0 & e_xe_z(1-cos\,\theta_0)+e_y\,sin\,\theta_0 \\ e_xe_y(1-cos\,\theta_0)+e_z\,sin\,\theta_0 & e_y^2(1-cos\,\theta_0)+cos\,\theta_0 & e_ye_z(1-cos\,\theta_0)-e_x\,sin\,\theta_0 \\ e_xe_z(1-cos\,\theta_0)-e_y\,sin\,\theta_0 & e_ye_z(1-cos\,\theta_0)+e_x\,sin\,\theta_0 & e_z^2(1-cos\,\theta_0)+cos\,\theta_0 \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} \quad (6)$$

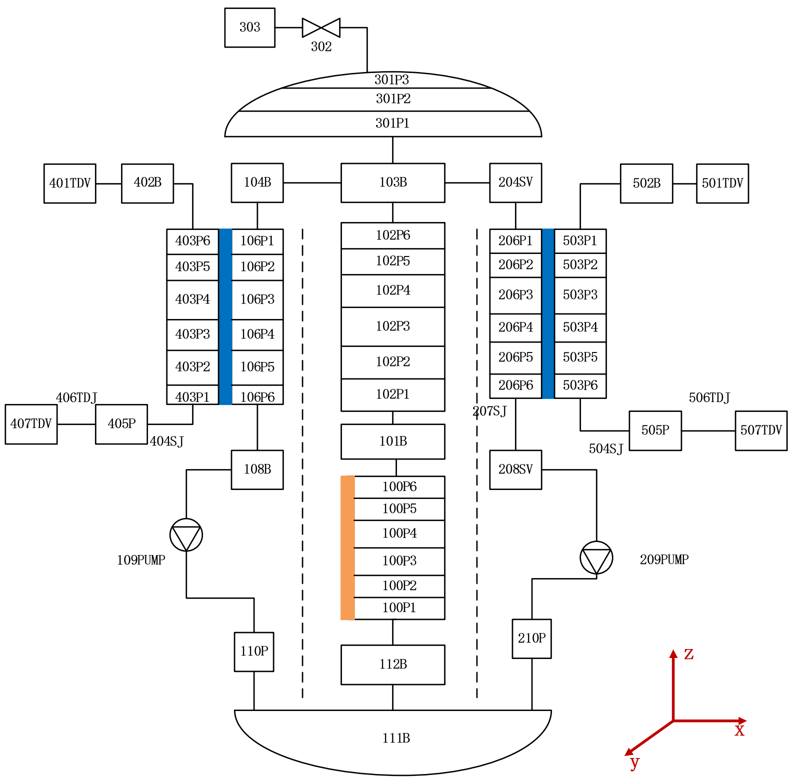

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Fig.1. Node diagram of small marine reactor

Table 1. main design parameters of small reactor

System parameter	Design value
Total power	240kW
Inlet temperature of core	564K
Outlet temperature of core	596.5K
Heated length	3.6576m
System pressure	15.5MPa
Mass flow rate of core	1182.7kg/s
Steam pressure	0.3MPa
Feed water temperature	406.8K

3.2 Results of normal operation under ocean condition

Full power operation driven by the main pump is simulated by the modified code in this section. Fig.2 portrays the fluctuation of mass flow rate caused by heaving motion. Under forced circulation condition, the additional heaving head is much smaller than the pump head, which makes little effect on the results. The instability increases by increasing the additional force that makes the program need a smaller time step during the calculation.

Here for inclining condition, y-axis as the rotation axle is analyzed for the height difference between core and steam generator is altered. Fig.3 shows the impact of inclination angle to the primary coolant mass flow rate, flow rate of two loops and core outlet temperature. It can be concluded that inclination reduces the total flow through the core and increases the core temperature. The impact to the left and right channel is opposite.

The flow and temperature variation with a rolling amplitude of 30° and period of 10s based on the y-axis rolling are shown in Fig.4. Unlike heaving and inclining, the influence is larger for each loop than for the core. The mass flow rate fluctuation of the two branches has a phase difference leading to the amplitude of flow through the core decrease with compensation. Besides, the impact of rolling angle on branch flow is also greater than that of inclination at the same angle. Compared Fig.3 to Fig.4, it can be seen that a 30° inclining causes a flow rate variation of up to 5kg/s, while a 30° rolling causes a flow rate fluctuation of 20kg/s amplitude in each channel.

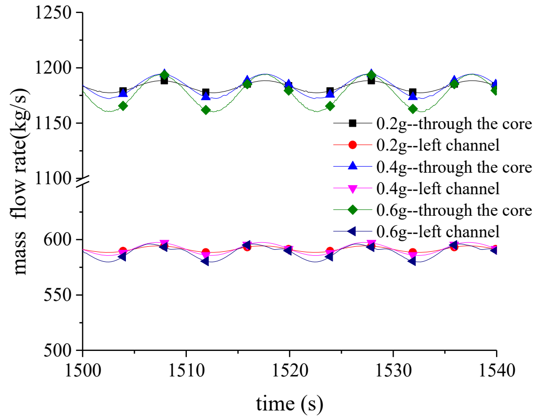


Fig.2. Mass flow rate under heaving condition

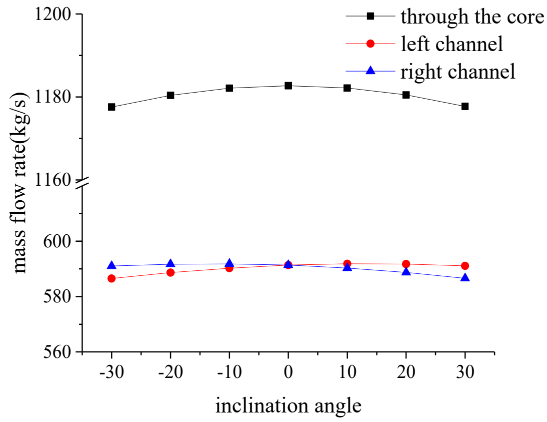


Fig.3. Mass flow rate under inclining condition

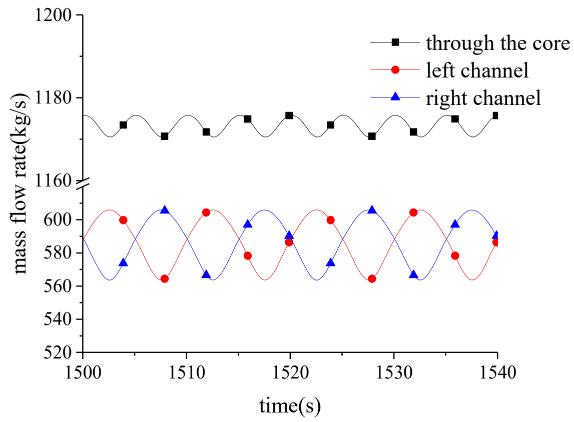


Fig.4. Mass flow rate under rolling condition (amplitude 30°, period 10s)

The composite motion of rolling and inclining is also calculated in this paper, and the comparison between rolling with and without inclination are depicted in Fig.5. Results illustrate that the amplitude of the fluctuation of one channel becomes larger and the other becomes smaller, and total flow of core is the superposition of multi-sinusoidal motions.

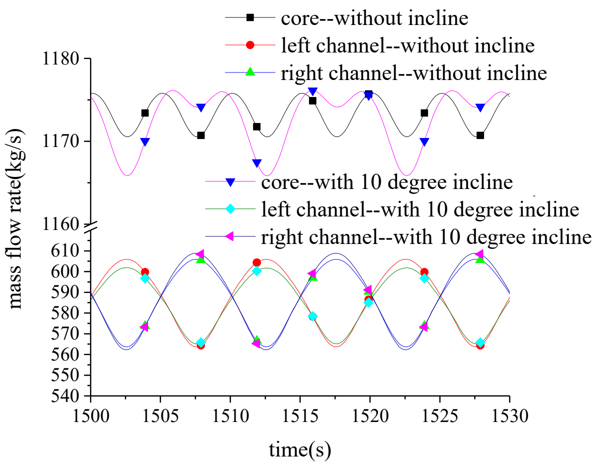


Fig.5. Superimposed effect of inclining and rolling

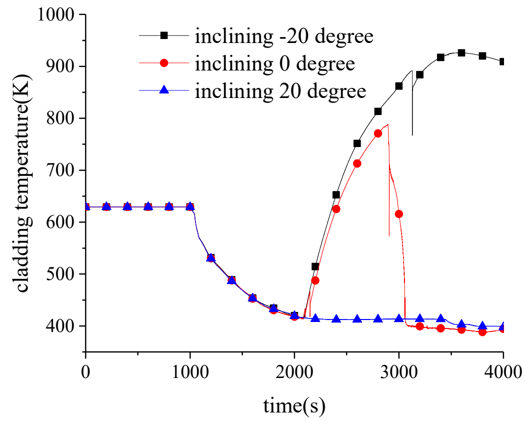


Fig.6. core outlet cladding temperature under inclining condition

4 Safety analysis of design basis accident

In the small reactor with forced circulation, the additional head caused by ocean motion is much smaller than the driving head of the pump which makes the influence relatively small, while for accident condition with termination of pump under natural circulation condition, the ocean motion may have more important impact.

First consider the simplified situation of small break loss of coolant accident (LOCA). It is assumed that a fracture occurs in the cold leg of left channel connected to pipe110 in Fig.1 with a diameter of 5cm after 1000s. When pressure drops below 12.82MPa, reactor shutdown, pump stop and ECC injection occurs successively with a time delay of 3.5s. In order to analysis the effect of ocean motion obviously, the safety injection flow rate of 10kg/s is chosen.

Fig.6 shows the cladding temperature variation for left-leaning and right-leaning of reactor system, where negative sign of angle presents for left inclination. It manifests the risk occurs when the inclination direction is the same with break channel. Fig.7 draws the effect of various rolling angle on cladding temperature. The peak cladding temperature becomes higher with increase of rolling amplitude in general.

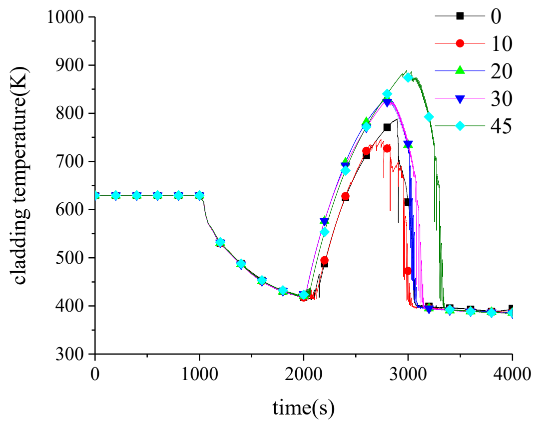
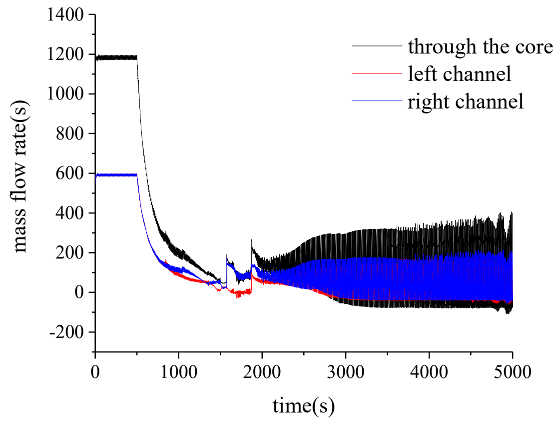
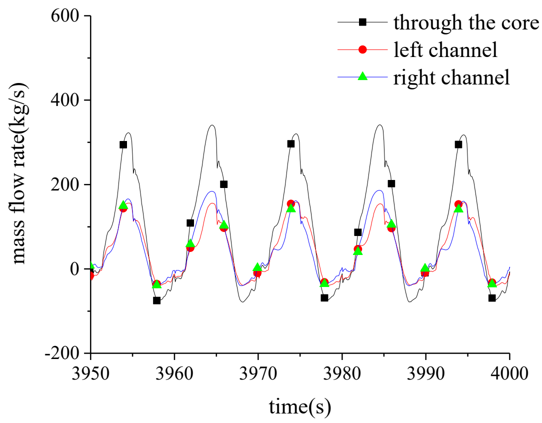


Fig.7. core outlet cladding temperature under rolling condition

The loss of flow accident (LOFA) is also simulated in this study. It is assumed that two main pump shutdown by power failure accident after 500s steady state operation, and the reactor shutdown is triggered when any one of the main pump speed is less than 90% of the rated speed. The flow rate change of LOFA can be divided into three stages, the first stage is the rapid drop of mass flow rate when the pump sets lose electricity, the second stage is stage of slow decline under the action of inert inertia of the pump and the third is natural circulation stage driven by density difference. Fig.8 and Fig.9 show the influence of heaving and rolling. The ocean motion may cause drastic fluctuation in the natural circulation stage. The fluctuation trend is similar as discussed before, but the amplitude is extremely large. However, the numerical instability of code may also be one reason of large oscillation, which should be verified by experiments in the future. Cladding temperature is stable reduced to the safety range which is less affected by the motions indicated in Fig.10.



(a) mass flow rate



(b) mass flow rate at 3950-4000s

Fig.8. Influence of heaving (0.4g)

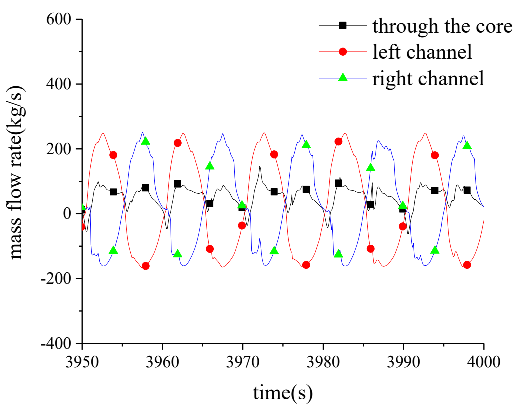


Fig.9. mass flow rate under rolling condition at 3950-4000s (amplitude 30°, period 10s)

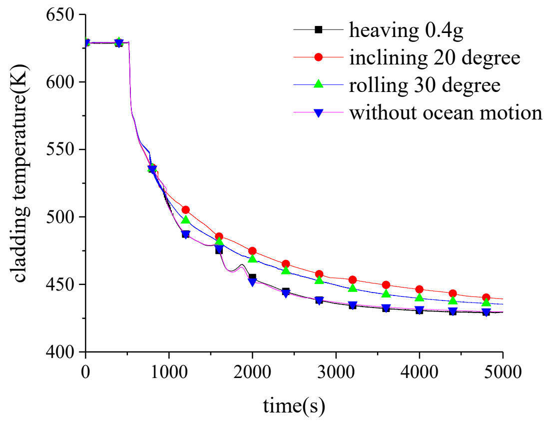


Fig.10. Cladding temperature under various ocean conditions

5 Conclusion

The impact of ocean motions, i.e. heaving, inclining and rolling on offshore small reactor are investigated through numerical simulation in this paper. The thermal hydraulic system code RELAP5 has been modified by additional forces introduced in the momentum equation and coordinate transformation.

Then a simplified model of small marine reactor with two loops is built by the modified code. Through the calculation and discussion of normal operation, small break LOCA and LOFA under ocean conditions, following conclusions could be obtained.

(1) The heaving motion will bring periodic oscillation of mass flow and the amplitude and the period are affected by the heaving acceleration. Due to the height difference between hot and cold sources, inclining and rolling will give rise to the increase or decrease of flow rate for each channel and the total flow through the core is reduced. The flow fluctuation of each loop has a phase difference, as the peak and valley of the wave compensate each other making the change of the total flow reduced.

(2) The inclination to the side of break may cause the accident more severe, while the inclination to the opposite direction may alleviate the accident and reduce the peak cladding temperature.

(3) The accident under rolling condition may bring drastic flow fluctuation, while it could be caused by the numerical instability of calculation need to be further verified.

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