Effect analysis of ship motions on marine small modular reactor under full power operation condition

CHENG Kun[1], MENG Tao[1], LIU Zheng[1], and TAN Sichao[1]

1. Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin 150001, China (chengkunhrbeu@sina.com; tansichao@hrbeu.edu.cn)

Abstract: Marine Small Modular Reactor (M-SMR) can effectively solve the offshore energy supply problem in marine resource development and island construction. Affected by ocean waves or other ocean conditions, the M-SMR can generate different kinds of ship motions, which can oscillate the thermal hydraulic parameters and threaten the reactor safety. Through adding ocean condition calculation module into the RELAP5 code, a reactor thermal-hydraulic system analysis code for M-SMR is developed. Effects of three typical ship motions (inclination, heaving and rolling) on the full power operation of a two-looped M-SMR is calculated. Results show M-SMR can keep safety operation under all assumed ocean conditions in present work. Heaving and rolling can cause the flow rate oscillation in both primary and secondary loops.

Keyword: system analysis code; ship motions; thermal-hydraulic; marine small modular reactor

1 Introduction

Energy shortage has become a big obstacle for ocean resource development in China. Floating nuclear power station is a ship-based floating platform equipped with Marine Small Modular Reactor (M-SMR) and it can be used to the electrical power provision, cogeneration and seawater desalination, which can effectively solve the problem of offshore energy supply [1]. Many countries, including Russia, China and the U.S., are actively engaged in the R&D of M-SMR [2-4].

Due to the influence of ocean waves or other ocean conditions, the ship-based floating platform can generate different kinds of ship motions, which can change the spatial positions of the reactor system and cause the system parameters fluctuation by introducing additional inertial force filed. Past researches had proved that the ship motions can change the characteristics of nuclear reactor thermal hydraulics and generate potential threats for the safe operation of M-SMR [5-8]. Therefore, the effects of the ocean condition on the full power operation of M-SMR must be considered.

Using thermal-hydraulic transient analysis code to simulate the behavior of reactor system is an effective method in the reactor safety analysis. However, most of the widely used system analysis codes, such as RELAP5, RETRAN and TRACE, are all designed for land-based reactors, which can hardly handle the simulation of M-SMR. Developing a motion condition, available thermal-hydraulic transient analysis code is one of the important parts for the R&D of M-SMR.

In the present study, through establishing the inertial acceleration models and adding ocean condition calculation module to RELAP5, a thermal-hydraulic system analysis code for M-SMR is developed. Effects of typical ship motions (inclination, heaving and rolling) on the full power operation of a two-looped M-SMR is calculated and analyzed.

2 Code Modification

As shown in Fig.1, there are typical ship motions caused by various ocean conditions. In order to describe the fluid flow under motion conditions, two right-handed Cartesian coordinates are introduced: the world coordinates ($O_0X_0Y_0Z_0$) located on the earth and the local coordinates ($O_1X_1Y_1Z_1$) located on the moving control volume.

Due to the ship motions mainly influent the momentum transfer, the modification of RELAP5 is conducted in its momentum equation. Equations (1) and (2) are the vapor phase and liquid phase momentum equations in expanded form, and in terms

Received date: November 1, 2018
(Revised date: January 10, 2019)

of momenta per unit volume used in RELAP5[9]. The six force terms on the right sides of these two equations are the pressure gradient, the body force, the wall friction, momentum transfer due to interface mass transfer, interface frictional drag, and force due to virtual mass, respectively.

$$\alpha_g\rho_g A\frac{\partial v_g}{\partial t}+\frac{1}{2}\alpha_g\rho_g A\frac{\partial v_g^2}{\partial x}=-\alpha_g A\frac{\partial P}{\partial x}+\alpha_g\rho_g B_x A-(\alpha_g\rho_g A)\mathrm{FWG}(v_g)+\Gamma_g A(v_{gI}-v_g)-(\alpha_g\rho_g A)\mathrm{FIG}(v_g-v_f)-C\alpha_g\alpha_f\rho_m A\left[\frac{\partial(v_g-v_f)}{\partial t}+v_f\frac{\partial v_g}{\partial x}-v_g\frac{\partial v_f}{\partial x}\right] \quad (1)$$

$$\alpha_f\rho_f A\frac{\partial v_f}{\partial t}+\frac{1}{2}\alpha_f\rho_f A\frac{\partial v_f^2}{\partial x}=-\alpha_f A\frac{\partial P}{\partial x}+\alpha_f\rho_f B_x A-(\alpha_f\rho_f A)\mathrm{FWF}(v_f)+\Gamma_g A(v_{fI}-v_f)-(\alpha_f\rho_f A)\mathrm{FIF}(v_f-v_g)-C\alpha_f\alpha_g\rho_m A\left[\frac{\partial(v_f-v_g)}{\partial t}+v_g\frac{\partial v_f}{\partial x}-v_f\frac{\partial v_g}{\partial x}\right] \quad (2)$$

The body force, such likes gravity or pump head, is referred to the term of B_x. The ship motions change the spatial position of M-SMR equipment and inflict accessional inertia acceleration. So modeling M-SMR under ship motions needs to model the changing coordinates of equipment and add inertial acceleration to the term of B_x.

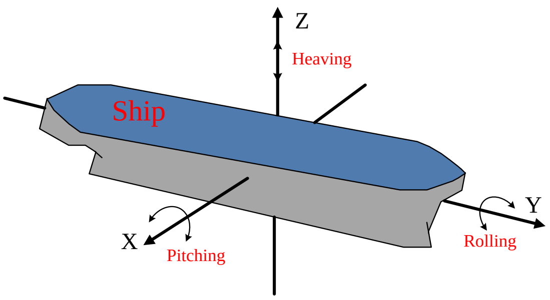

Fig.1 Typical ship motions under ocean condition

2.1 Stationary Inclination Model

The stationary inclination of ship includes two kinds of motions, namely heeling and trimming, which all change the spatial coordinates of hydrodynamic components and the thermal driving head of nature circulation. The new coordinate of control volumes after inclination can be calculated by the rotation matrix (3):

$$\begin{bmatrix}x_1\\y_1\\z_1\end{bmatrix}=\begin{bmatrix}\cos r & -\sin r & 0\\ \sin r & \cos r & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\cos\beta & 0 & \sin\beta\\ 0 & 1 & 0\\ -\sin\beta & 0 & \cos\beta\end{bmatrix}\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\alpha & -\sin\alpha\\ 0 & \sin\alpha & \cos\alpha\end{bmatrix}\begin{bmatrix}x_0\\y_0\\z_0\end{bmatrix} \quad (3)$$

Where (x_0, y_0, z_0) is the original coordinate of control volume in the world coordinates. α, β, γ are the angles inclining around the X_0, Y_0, Z_0 axis of the world coordinates respectively. The new coordinate of the inclined component can be got as (x_1, y_1, z_1).

2.2 Heaving Model

Heaving motion gives ships a time-dependent vertical acceleration, which can be expressed as equation (4). The original gravity acceleration $\vec{g}_0$ in the term of B_x needs to be replaced by the new vertical acceleration in momentum equation of RELAP5.

$$\vec{g}' = \vec{g}_0 - \vec{a}(t) = \vec{g}_0 + A\sin\left(\frac{2\pi t}{T}\right)\vec{k} \quad (4)$$

Where A is the heaving amplitude and T is the heaving period.

2.3 Rolling Model

Rolling refers to a kind of rotational reciprocation motion around a certain axis, which can be expressed by following equations (5):

$$\text{Rolling angle:} \quad \theta(t)=\theta_m\sin\left(\frac{2\pi t}{T}\right)$$

$$\text{Angular velocity:} \quad w(t)=\frac{2\pi\theta_m}{T}\cos\left(\frac{2\pi t}{T}\right) \quad (5)$$

$$\text{Angular acceleration:} \quad \beta(t)=-\frac{4\pi^2\theta_m}{T^2}\sin\left(\frac{2\pi t}{T}\right)$$

Where θ_m is the amplitude of rolling angle and T is the period of rolling motion.

As shown in Fig.2 (a), rolling not only changes the spatial position of hydrodynamic components, but also generates centrifugal acceleration, $a_c = w^2 R$ and tangential acceleration, $a_t = \beta R$.

Supposing control volume, P, rolls around Y_0 axis, as shown in Fig.2 (b), the centrifugal and tangential accelerations can be expressed as equation (6):

$$\alpha_c = w^2\sqrt{R_x^2+R_y^2} \qquad \alpha_t = \beta\sqrt{R_x^2+R_y^2} \quad (6)$$

where (R_x, R_y, R_z) refers to new coordinates of the control volume after rolling, which can be obtained by the same way of inclination calculation.

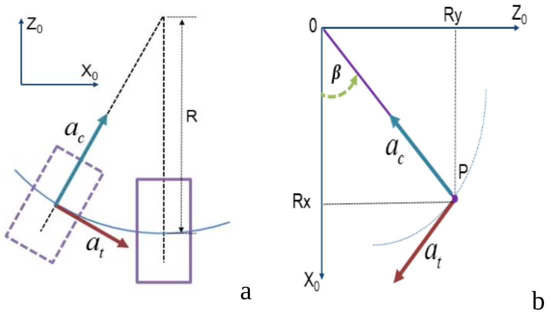

Fig.2 Accelerations under rotation around Y0 axis.

Similarly, the centrifugal and tangential accelerations of rotation around X_0, Z_0 axis can be obtained. Then the inertial accelerations of rolling motion can be expressed as equation (7) and equation (8):

$$\begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} = \begin{bmatrix} (w_z^2 + w_y^2) & \beta_z & -\beta_y \\ -\beta_z & w_z^2 + w_x^2 & \beta_x \\ \beta_y & -\beta_x & w_y^2 + w_x^2 \end{bmatrix} \begin{bmatrix} R_x \\ R_y \\ R_z \end{bmatrix} \quad (7)$$

$$\vec{\alpha}_{roll} = -\alpha_x \vec{i} - \alpha_y \vec{j} - \alpha_z \vec{k} \quad (8)$$

2.4 RELAP5 Modification

Based on the above analysis, the modification of RELAP5 under ship motions are mainly calculating new spatial coordinates of hydrodynamic components and adding accessional inertia acceleration to the momentum equation of RELAP5. Considering the inertia forces caused by ocean condition has the similar characteristics with the gravity, the inertia accelerations can be directed along the three axes of the world coordinates and be introduced to the momentum equation of RELAP5 by the same processing methods as the gravity. The processed equivalent acceleration, $\vec{\alpha}_i$, can be expressed as follows:

$$\vec{\alpha}_i = -a_x \vec{i} - a_y \vec{j} + (g_0 - a_z)\vec{k} \quad (9)$$

where the a_x, a_y, a_z are the components of inertial acceleration under motion conditions directing the positive direction of three axes in the world coordinates.

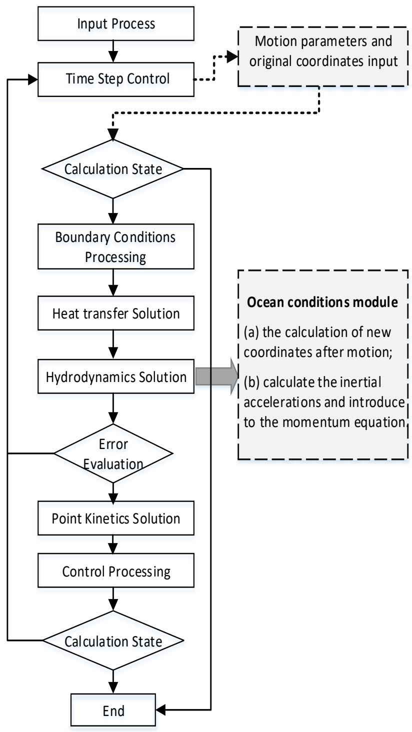

Fig.3 Flowchart of modified RELAP5 transient calculation.

Since the main calculation progress of RELAP5 conducts in its transient processing subroutines, the modification scheme is calculating the new spatial position and introducing new inertial accelerations before every time step of transient calculation of RELAP5. Figure 3 is the flow chat of modified RELAP5 transient calculation.

The experimental validation for the developed RELAP5 code was conducted in another research work, as shown in reference [10]. Experimental data obtained by zero power loading experiment and single-phase natural circulation experiment under rolling motion are used to verify the ocean condition theoretical models as well as the code modification strategy. Results show that the flow fluctuation behaviors caused by rolling motion can be well simulated by the developed code. The calculation capability of modified RELAP5 code under static inclining and heaving motion is also verified by comparing with RETRAN-02/GRAV code.

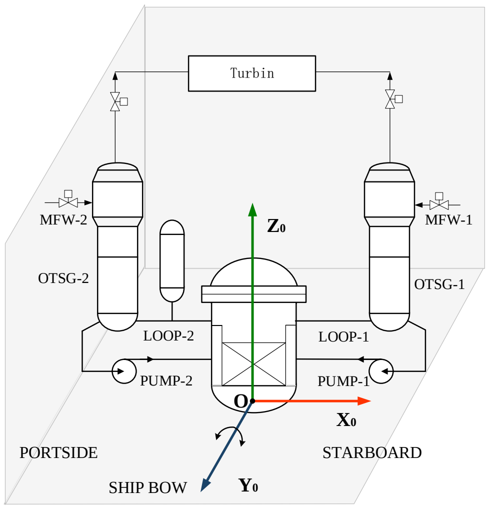

Fig.4 RELA5 Nodalization of two-looped M-SMR mode4 Results and Discussion.

3 M-SMR Model and Description

Referring to the existing concept and design, a RELAP5 model for a two-looped M-SMR was established, which includes a reactor pressure vessel (PRV), two main coolant pumps (MCPs), two helical coiled once-through steam generators (OTSGs) and other necessary facilities. And the nodalization scheme is shown in Fig.4. Supposing the M-SMR model is located in a ship and the negative direction of Y_0 axis points to the ship bow. Major parameters about the M-SMR model is reported in table1.

Table 1 Main parameters of M-SMR model

Main parameters	Value
Reactor rated power (MWt)	200
Primary operation pressure (MPa)	15
PRV inlet/outlet temperature (K)	577/600
Core flow rate (kg/s)	1470
OTSG steam pressure (MPa)	4.8
OTSG steam flow rate (kg/s)	4.0

The reactor is operated at full power condition and two main pumps drive the primary coolant to flow through the reactor core and exchange heat with the secondary loops by OTSGs. In the present study, the main feedwater is controlled by a time depend on the junction and keeps constant flow rate and temperature. Calculations and analysis have been performed under both static condition and motion conditions. All calculation results are normalized by their static value.

4 Results and Discussion

4.1 Effects of Stationary Inclination

The effect of heeling (inclining around the Y_0 axis) on M-SMR full power operation was calculated and analyzed in present work. Figure 5 shows the normalized system pressure in the case of heeling of 15°. The core pressure and the secondary loop pressure show almost constant values which indicates the system pressure cannot be affected by heeling.

As shown in Fig.6, though the core flow rate under heeling is almost the same with its static value, the difference of flow rate between two primary loops is apparent. In the case of 15° heeling condition, the change of vertical distance between the reactor core and two OTSGs leads to the difference of natural circulation driving head of two primary loops. For the Loop1 which connecting with the OTSG-1 in Fig.4, the full power operation flow rate is weakened by the reduction of natural circulation ability. But for the Loop2 which connecting with the OTSG-2, the flow rate is enhanced by the increasing of nature circulation ability. Compared with the change of flow rate in the primary loops, the 15° heeling of M-SMR has no influence on the steam flow rate of two OTSGs. The PRV inlet and outlet temperature show almost constant value with their static value (Fig.7).

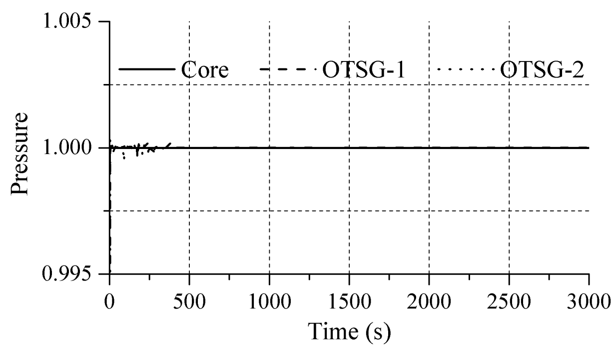

Fig.5 Normalized system pressure of M-SMR under 15°heeling.

Based on the above results, it is shown that the heeling of 15° cannot generate substantial effects on the full power operation of the M-SMR model in present research. The big pump head offsets the influence of natural circulation flow rate change and provides a stable operating condition. However, for some natural circulation cooled SMRs or some accident conditions (like Station Black Out), the effects of stationary inclination on the reactor safety needs to be further studied.

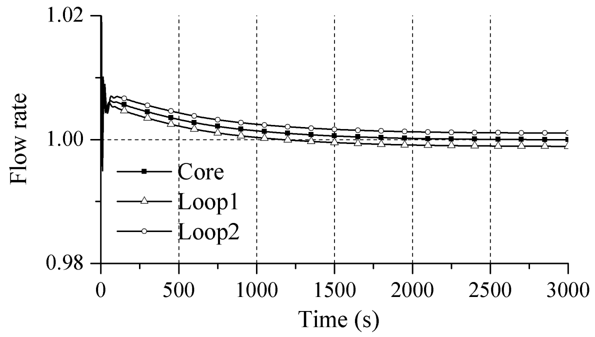

Fig.6 Normalized flow rate of the primary loops under 15 ° heeling.

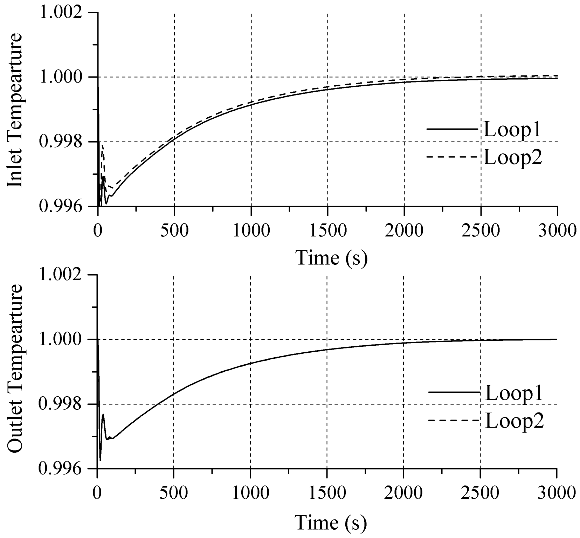

Fig.7 Normalized PRV inlet and outlet temperature under 15 ° heeling.

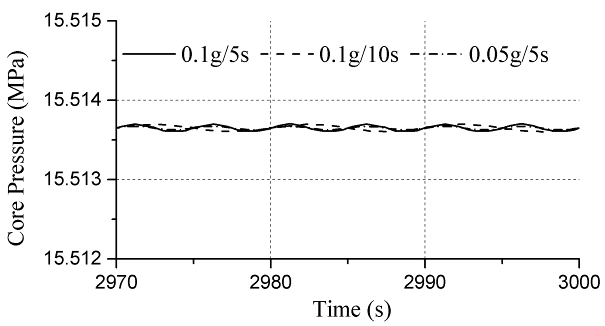

Fig.8 Core pressure of M-SMR under heaving conditions.

4.2 Effects of Heaving

The operation characteristic of M-SMR under different heaving magnitude and period was calculated and analyzed. In the full power operation condition, heaving motion cannot cause apparent oscillations of core pressure (Fig.8).

As shown in Fig.9, the flow rate of the primary loop oscillates with the same period of heaving and this kind of flow rate oscillation becomes larger by increasing the magnitude of heaving motions. Keeping the heaving magnitude as a constant value (0.1g) and changing the heaving period from 10s to 5s, the flow rate oscillation level shows no difference.

Figure 10 shows the variation of the steam flow rate in OTSG-1. The oscillation period of the steam flow rate is also the same with the heaving period. Due to the lower density for steam, the changing vertical acceleration has a lower influence on the steam flow rate than that in the primary loop. Different from the response of the primary loop flow rate, increasing the heaving magnitude and period can both enhance the flow rate oscillation. Though the primary loop flow rate presents apparent oscillation, the variation of coolant temperature in the inlet and outlet PRV nozzles are negligibly small (Fig.11).

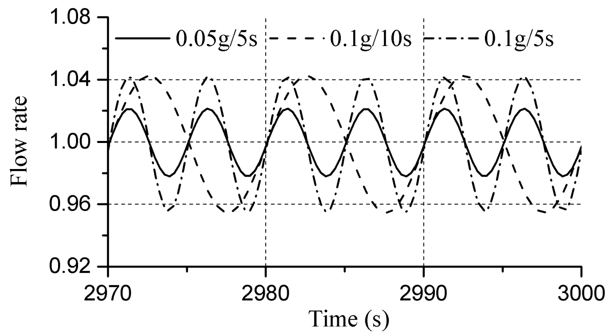

Fig.9 Normalized flow rate of Loop1 under heaving conditions.

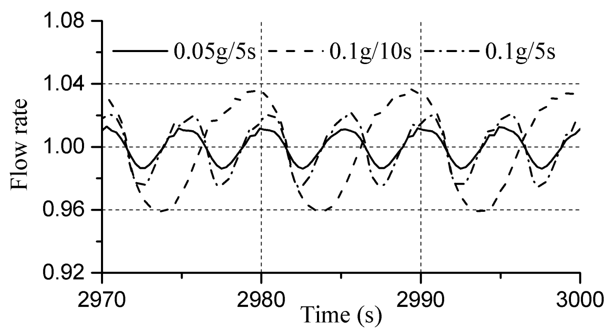

Fig.10 Normalized steam flow rate of OTSG-1 under heaving conditions.

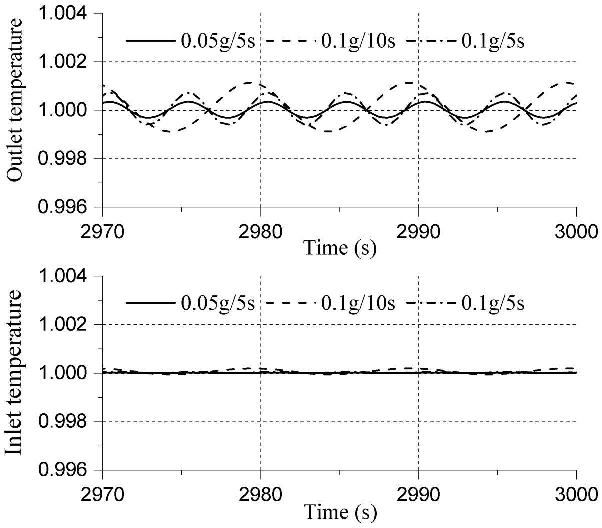

Fig.11 Normalized PRV inlet and outlet temperature under heaving conditions.

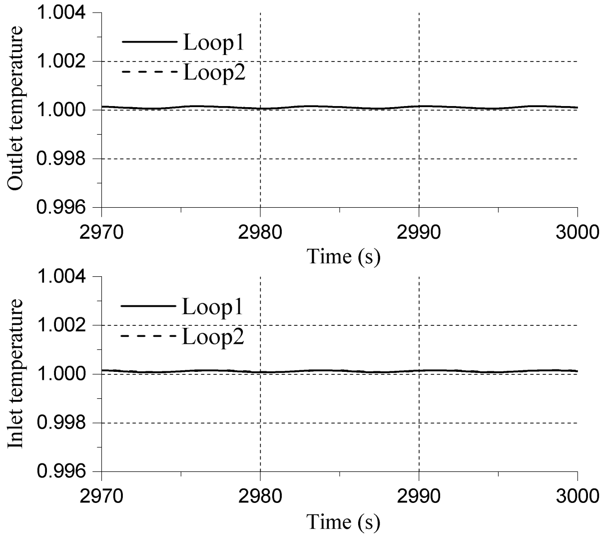

Fig.13 Normalized PRV inlet and outlet temperature under rolling condition (Amplitude 22.5 °, Period 7.0s).

4.3 Effects of Rolling

The ship rolling (around the Y_0 axis) can inflict accessional inertia force and affect the full power operation of M-SMR. In the present work, the angle of 22.5 °was assumed as the maximum rolling amplitude, and two rolling periods (7.0s and 14.0s) was calculated to study the effects of the different rolling period. The axis of rolling is located in the bottom of PRV of M-SMR model (Fig.4).

Figure 12 and 13 show the calculation results of core pressure and coolant temperature under rolling motions respectively. The effects of the ship rolling on system pressure and coolant temperature in the full power operating condition are negligible.

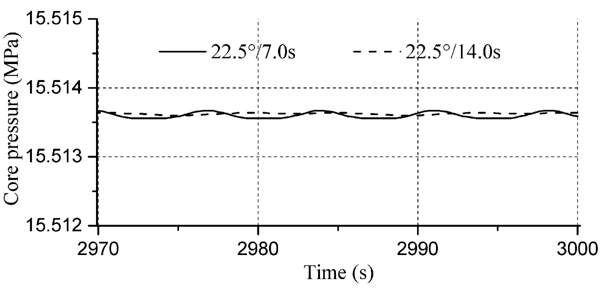

Fig.12 Core pressure of M-SMR under rolling conditions.

The rolling motion can lead to the flow rate fluctuation in the primary loop. As shown in Fig.14, oscillation period of loop flow rate under rolling is the same as its motion period. The fluctuation phase position of flow rate for Loop1 and Loop2 is opposite. Increasing rolling period can weaken the flow rate fluctuation in a single primary loop. But for the core flow rate, the effects of rolling are really small and the core flow rate can keep stable under motion conditions in the present study. Same variation trend can be also found in the steam flow rate in OTSGs (Fig.16). Different from the behavior of the primary loop flow rate, the effects of rolling period change on steam flow rate is indistinctive.

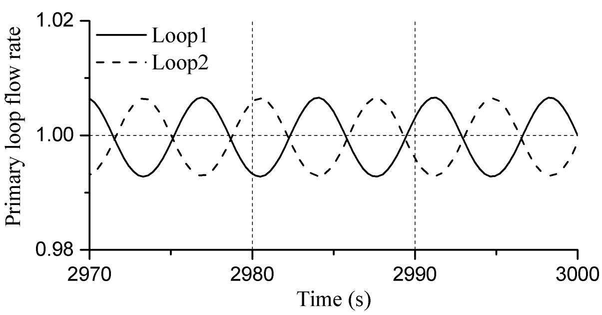

Fig.14 Normalized flow rate of the primary loops under rolling condition (Amplitude 22.5 °, Period 7.0s).

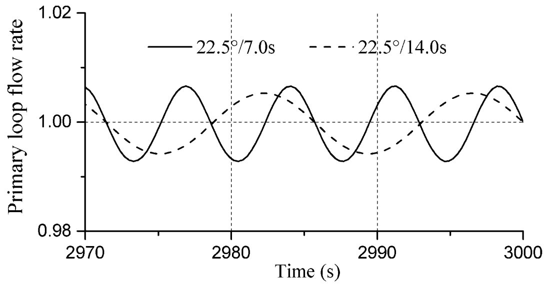

Fig.15 Normalized flow rate of Loop1 under different rolling conditions.

The effects of different rolling axis positions on the flow rate oscillation are shown in Fig.17. Results show that the flow rate oscillation in the primary loop is strengthened by changing the rolling axis from the top of RPV to the bottom. Just as analyzed in the above section, the centrifugal force and tangential force caused by rolling are both functions of the distance from the control volume to the axis of rolling. Compared to the bottom of RPV, rolling axis located in the top of RPV is more close to the geometric center of the whole reactor system, which can not only decrease that distance but also partially offset the additional inertial force.

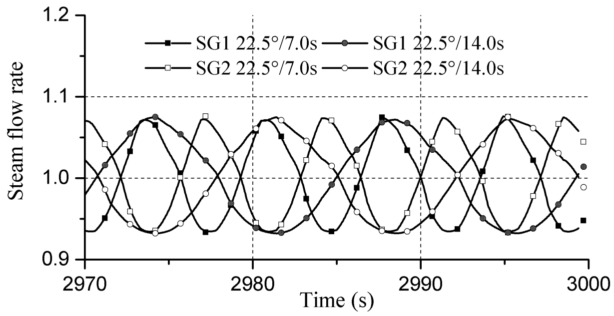

Fig.16 Normalized steam flow rate of OTSGs under different rolling conditions.

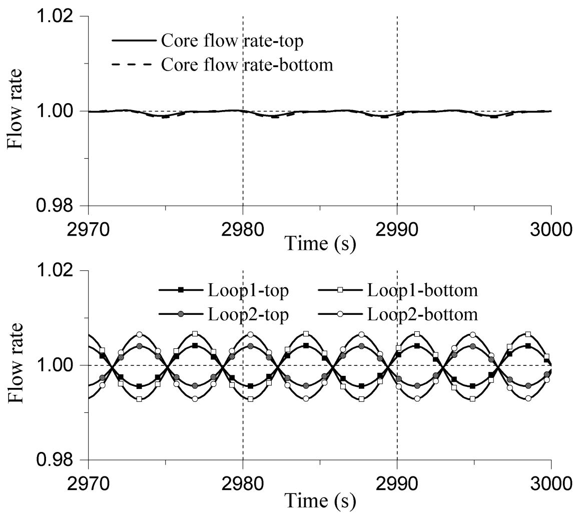

Fig.17 Effects of different rolling axis positions on the flow rate oscillation.

5 Conclusion

Based on the force analysis, the inertial acceleration model under ship motions was established. A ship motion condition available thermal-hydraulic analysis code based on RELAP5 was developed. The effects of ocean condition on the full power operation of a two-looped M-SMR model were studied. Results can be concluded as follows:

1) The M-SMR can operate stably in the case of heeling of 15 °. Inclination cannot cause apparent influence on the system parameters such as core pressure and PRV inlet or outlet temperature. Due to the change of natural circulation ability, a small difference of flow rate for two primary loops was found in the present study. Therefore, the effects of inclination on the natural circulation cooled M-SMR or some accident conditions such as SBO need to further study.
2) Heaving motion can cause the fluctuation of flow rate in both primary and secondary loops. Changing heaving amplitude or period can change the behavior of flow rate oscillation. In the full power operation condition, core pressure and reactor temperature keep constant as their static value.
3) In full power operation, rolling motion lead to the opposite phase-position oscillation of flow rate in both the primary and secondary loops. Increasing the rolling period can make a more stable flow in the primary side. The main system parameters such as core flowrate, core pressure, and reactor temperature keep stable under rolling motions. The reasonable arrangement of M-SMR equipment which makes the rolling axis more close to the system geometric center can reduce the influence of ship rolling.

Acknowledgment

This work is financially supported by National Key R&D Program of China (2017YFE0106200) and the Youth Leading Scholar Supporting Program in General Colleges and Universities of Heilongjiang Province (1254G017).

References

[1] LEE, K., KIM, M., and LEE, J.I., *et al.*: Recent Advances in Ocean Nuclear Power Plants, Energies, 2015, 8(10): 11470-11492.

[2] BUONGIORNO, J., JUREWICZ, J., and GOLAY, M.W., *et al.*: The Offshore Floating Nuclear Plant Concept, Nuclear Technology, 2016, 194(1): 1-14.

[3] LEE, K., LEE, K.H., and LEE, J.I., *et al.*: A New Design Concept for Offshore Nuclear Power Plants with Enhanced Safety Features, Nuclear Engineering and Design, 2013: 129-141.

[4] KOSTIN, V.I., PANOV, Y.K., and POLUNICHEV, V.I., *et al.*: Floating Power-Generating Unit with A KLT-40S Reactor System for Desalinating Sea Water. Atomic Energy, 2007, 102(1): 31-35.

[5] ISHIDA, T., KUSUNOKI, T., and OCHIAI, M., *et al.*: Effects by Sea Wave of Thermal Hydraulics of Marine Reactor System, Journal of Nuclear Science and Technology, 1995, 32(8):740-751.

[6] ISSHIKI, N.: Effects of Heaving and Listing Upon Thermo-Hydraulic Performance and Critical Heat Flux of Water-Cooled Marine Reactors, Nuclear Engineering and Design, 1966, 4(2):138-162.

[7] ISHIDA, T., and YORITSUNE, T.: Effects of Ship Motions on Natural Circulation of Deep Sea Research Reactor DRX, Nuclear Engineering and Design, 2002, 215(1):51-67.

[8] YAN, B.H.: Review of The Nuclear Reactor Thermal Hydraulic Research in Ocean Motions, Nuclear Engineering and Design, 2017, 313:370-385.

[9] CARLSON, K., RIEMKE, R., and ROUHANI, S., *et al.*: RELAP5/MOD3 Code Manual Volume I: Code Structure, System Models and Solution Methods. Washington (DC, USA): US NRC NUREG/CR-5535, 1990.

[10] KUN, C., TAO, M., and FU, L.Z., *et al.*: Development and Validation of a Thermal Hydraulic Transient Analysis Code for Offshore Floating Nuclear Reactor Based on RELAP5/SCDAPSIM/MOD3.4, Annals of Nuclear Energy, 2019, 127:215-226.