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Development of RETRAN-03/MOV Code for Thermal-Hydraulic Analysis of Nuclear Reactor Under Moving Conditions

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Abstract

Nuclear ship reactors have several features different from land-based PWR's. Especially, effects of ship motions on reactor thermal-hydraulics and good load following capability for abrupt load changes are essential characteristics of nuclear ship reactors.

This study modified the RETRAN-03 to analyze the thermal-hydraulic transients under three-dimensional ship motions, named RETRAN-03/MOV in order to apply to future marine reactors. First Japanese nuclear ship MUTSU reactor have been analyzed under various ship motions to verify this code. Calculations have been performed under rolling, heaving and stationary inclination conditions during normal operation. Also, the natural circulation has been analyzed, which can provide the decay heat removal to ensure the passive safety of marine reactors. As results, typical thermal-hydraulic characteristics of marine reactors such as flow rate oscillations and S/G water level oscillations have been successfully simulated at various conditions.

1. Introduction

Nuclear ships have outstanding advantages such as long-period navigation with high power and long-period underwater navigation that are regarded as difficult in conventional ships. At present, nuclear ships are not expected to be applied immediately for practical use mainly from economic aspects. However, in the future, there is a lot of potential that the need of nuclear ships would be realized according to the changes in economic and social circumstances based on the expected shortage in fossil fuel. Thus research and development on nuclear ship reactors are strongly required. The previous researches in this field are quite limited to assess due to military security or ship reactor company proprietary. Several analytical and experimental studies for the effect of heaving on the critical heat flux[1] and the effect of heaving or rolling on the natural circulation flow[2] have been published. And JAERI developed RETRAN-02/GRAV code[6], which is the modified version of RETRAN-02 code[4], to simulate the experimental voyages of the first Japanese nuclear ship, MUTSU [3][7].

Thermal-hydraulic characteristics of marine reactor plants are influenced by various ship motions. There are six ship motions caused by various sea conditions, which are three linear motions(heaving, swaying, surging) and three rotational motions(rolling, pitching, yawing). Stationary inclination, heaving and rolling are dominant in ship motions and very important for design and operation of nuclear ship reactors. In this study, since it is impossible to analyze such thermal-hydraulic transients under various ship motions using current thermal -hydraulic analysis codes for land-based reactors, the RETRAN-03 code[5] is modified so as to be capable of simulating systematic thermal-hydraulic transients under multi-dimensional ship motions. The modified version is named as RETRAN-03/MOV, where gravity head terms are modified and new head terms for acceleration forces and transformation of coordinates caused by ship motions are added. With this code, MUTSU reactor has been analyzed under various ship motions for its validation. Simulations of rolling, heaving and stationary inclination conditions during the normal operation have been performed. Also, the natural circulation has been analyzed, which can provide the decay heat removal in case of pump shutdown to ensure the passive safety of marine reactors.

Results have been compared with some available data from JAERI analysis[6]. Even though there were discrepancies for some variables due to the lack of informations, the trend and quantities of most variables showed good agreements and typical thermal-hydraulic characteristics of marine reactors such as flow rate oscillation and S/G water level oscillations have been successfully simulated at various conditions.

2. RETRAN-03 Modification

The RETRAN-03 code is a well-known design code for transient thermal-hydraulic analysis of complex reactor systems. It is a one-dimensional system analysis code and there is no consideration of multi-dimensional motions. Thus, the modification of RETRAN-03 is to develope a code, named as RETRAN-03/MOV, for thermal-hydraulic analysis of nuclear ship reactors under multi-dimensional motions.

2.1. Momentum Equation of RETRAN-03

Since ship motions affect on the momentum transfer, especially for the natural circulation, the modification is mainly implemented for the momentum equation. The nodalized integral momentum for i-th momentum cell in RETRAN-03 is given as[5],

$$\frac{1}{2}\left[\frac{L_k}{A_k}+\frac{L_{k+1}}{A_{k+1}}\right]\frac{dW_i}{dt}=\frac{\overline{w}^2{}_k}{\rho_k A_k^2}-\frac{\overline{w}^2{}_{k+1}}{\rho_{k+1}A_{k+1}^2}$$
$$+p_k-p_{k+1}-\frac{1}{A_k}F_{w,k}-\frac{1}{A_{k+1}}F_{w,k+1}-(\varDelta p)_p \quad (1)$$
$$-[\ \overline{\rho}_k(Z_i-Z_k)+\overline{\rho}_{k+1}(Z_{k+1}-Z_i)]g_z$$

For the modelling of multi-dimensional moving motions, the gravity head term(8th term of right hand side) in above equation must be modified. Gravity should be treated as a time dependent function and acceleration forces induced by ship motions should be included in gravity head terms. And models for changes of co-ordinates in x, y, z directions during rotational motions should be added.

2.2. Mom. Equation Under Heaving Motion

To take account of the time dependent vertical acceleration of gravity force, g_z in Eq. 1 is replaced with time dependent gravity g(t). For the simple periodical oscillation, g(t) can be expressed as,

$$g(t)\ =\ g_z\left(1\ +\ A*\sin\left(\frac{2\pi t}{T_g}\right)\right) \quad (2)$$

where, A = *amplitude*

T_g = *oscillation perioa*

2.3. Mom. Equation Under Rolling Motion

Rolling is a rotational motion which generates a time dependent centrifugal and tangential forces, f_c and f_t, on the plant system. Each forces on the fluid volume under rolling is depicted in Fig. 1. For the given rotational angle θ_y about y-axis(positive direction is a rotation from z to x-axis) as a function of time, vertical and horizontal components of centrifugal(C_z, C_x) and tangential forces(T_z, T_x) are calculated as follows,

$$\begin{aligned} C_z &= R\ \dot{\theta}_y^{\,2}\cos\theta_y\ , & C_x &= R\ \dot{\theta}_y^{\,2}\sin\theta_y \\ T_z &= R\ \ddot{\theta}_y\sin\theta_y\ , & T_x &= R\ \ddot{\theta}_y\cos\theta_y \end{aligned} \quad (3)$$

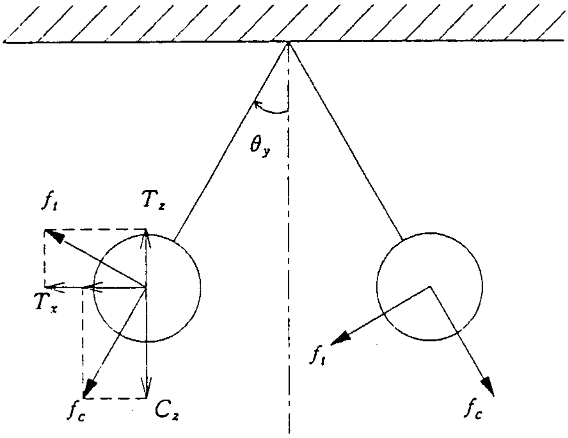


Fig. 1. Centrifugal and Tangential Forces During Rolling Motion

where, R is a distance between volume center and center of rotation.

These forces can be divided into the vertical and the horizontal components, f_z and f_x as follows,

$$\begin{aligned} f_z &= C_z - T_z = R\,\dot{\theta}_y^{\,2}\cos\theta_y - R\ddot{\theta}_y\sin\theta_y \\ f_x &= C_x + T_x = R\,\dot{\theta}_y^{\,2}\sin\theta_y + R\ddot{\theta}_y\cos\theta_y \end{aligned} \tag{4}$$

For the simulation of 3-D motions, 3 dimensional control volume is considered as depicted in Fig. 2. Differently from 1-D pipe control volumes of hot/cold legs in RETRAN-03, in this study, the complicate geometries of hot and cold legs are represented with a single pipe but having different positions of inlet and outlet. To simulate this different inlet and outlet positions, a new variable BOT, which indicates the volume length in the horizontal direction, is considered. According to this model, locations of center of mass and each junctions after rotation can be calculated as follows,

$$\begin{aligned} CMAS_{k+1}' &= CMAS_{k+1}\cos\theta_y \\ RELZ_i' &= RELZ_i\cos\theta_y + 1/2\ BOT_{k+1}\sin\theta_y \\ RELZ_{i+1}' &= RELZ_{i+1}\cos\theta_y - 1/2\ BOT_{k+1}\sin\theta_y \end{aligned} \tag{5}$$

Also, the variation of water level can be expressed as a function of rolling angle as follow,

$$ZM' = ZM\cos\theta_y \tag{6}$$

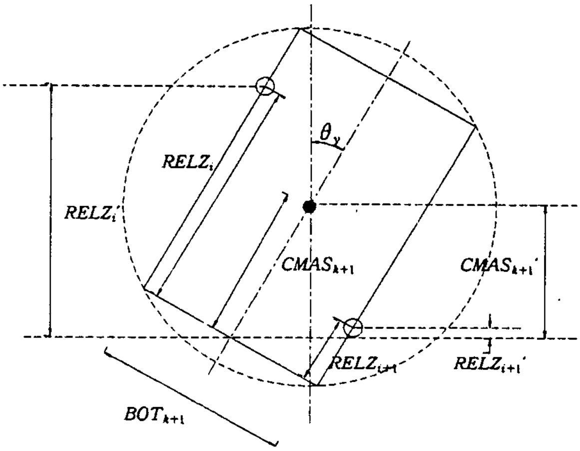


Fig. 2. Center of Volume and Junction Elevation at Inclination

According to this model, modified values of Z_i, Z_k, and Z_{k+1} can be calculated.

$$\begin{aligned} Z_i' - Z_k' &= RELZ_i' - CMAS_k' \\ Z_{k+1}' - Z_i' &= CMAS_{k+1}' - RELZ_i' \end{aligned} \tag{7}$$

Considering above equations, body force terms are made up of gravity head term, x- and z-direction accelerational terms by centrifugal and tangential forces between center of volume and each junction. Therefore, modified integral momentum equation is as,

$$\begin{aligned} \frac{1}{2}\left(\frac{L_k}{A_k}+\frac{L_{k+1}}{A_{k+1}}\right)\frac{dW_i}{dt} &= \frac{\overline{w}^2{}_k}{\rho_k A_k^2} - \frac{\overline{w}^2{}_{k+1}}{\rho_{k+1}A_{k+1}^2} \\ &+ p_k - p_{k+1} - \frac{1}{A_k}F_{w,k} - \frac{1}{A_{k+1}}F_{w,k+1} - (\Delta p)_p \\ &- (\overline{\rho}_k(Z_i'-Z_k') + \overline{\rho}_{k+1}(Z_{k+1}'-Z_i'))(g(t)+f_z) \\ &- \frac{1}{2}(\overline{\rho}_k\ BOT_k\cos\theta + \overline{\rho}_{k+1}BOT_{k+1}\cos\theta)\ f_x \end{aligned} \tag{8}$$

where, Z_i'-Z_k', $Z_{K+1}'-Z_i'$ are calculated from Eq. 7, g(t) is from Eq. 2, f_x, f_z are from Eq. 4, and θ_y, BOT_k, BOT_{k+1} are from input decks.

The 8-th term of right hand side represents the consideration of the vertical acceleration change from the heaving and rolling motion. The 9-th term accounts for the acceleration in horizontal direction of ship motions.

2.4. Modifications of Input Decks

Volume data input cards should be modified in order to calculate the changes of position and acceleration forces under 3-D motions. New Variables indicating distances between volume center and center of rotation and volume lengths mapped on the x and y axes are added. Rotation angles are calculated from Control Block Function in RETRAN-03/MOV. For the calculation of these angles, input variables indicating Control Block Function number which calculates rotation angle for each time step should be added in General data input cards(12XXXY). Using these input variables, rotation angles can be made as a function of time. Centrifugal and tangential forces are computed using these time derivatives of rotation angle as well as the distance from the center of rotation.

3. Results and Discussions

Thermal-hydraulic behaviors of first Japanese nuclear ship 'MUTSU' reactor have been analyzed. The nuclear powered ship 'MUTSU' reactor is a two looped PWR with a 36 MWt rated reactor power. Fig. 3 show the RETRAN-03/MOV computational nodalization for MUTSU reactor analyses. Calculations have been performed under both normal operation and natural circulation conditions.

3.1. Normal Operation

3.1.1. Effects of Heaving

Fig. 4(a) shows S/G secondary side behaviors during the heaving motion for various heaving period.

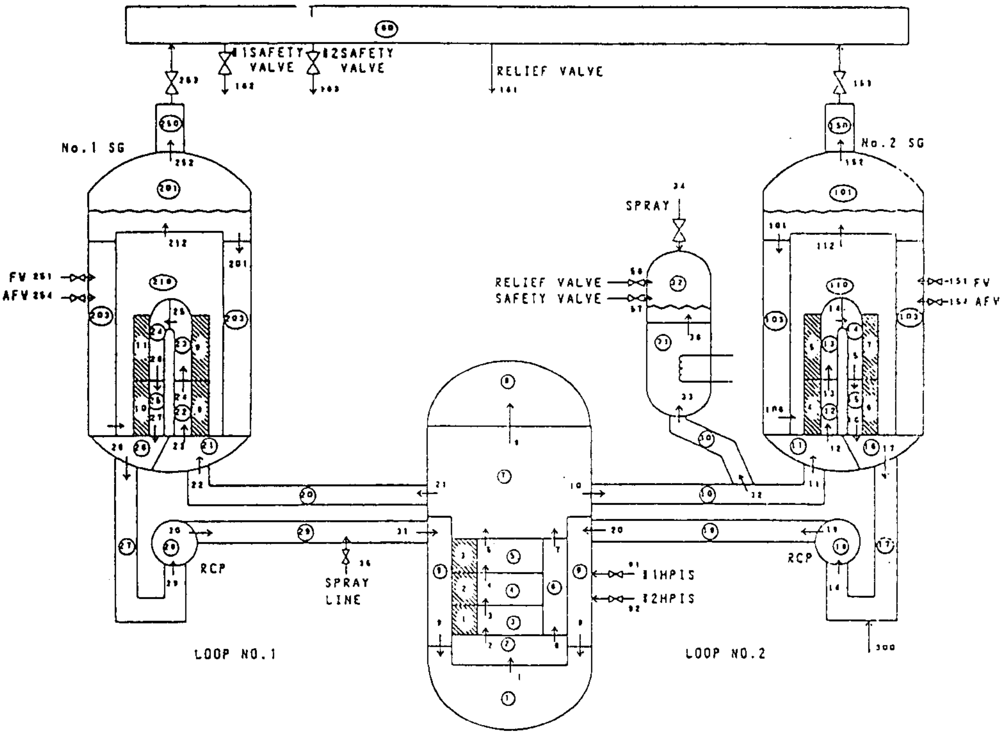


Fig. 3. MUTSU Reactor Computational Nodalization for RETRAN-03/MOV Analysis

During 70% normal operation, the magnitude of gravity oscillation is 0.6g and oscillation periods are set to 4, 15, 30 seconds.

As the gravity force increases, the steam generator water level decreases. And the longer oscillation period results in larger variations of the S/G water level. Since the steam generator secondary side flow is in a two phase natural circulation state, magnitudes of S/G water level and recirculation flow oscillations are determined by slip ratio and flow resistance. Therefore, vertical movement of reactor such as heaving cause larger value of water level oscillation than rolling motion. However, the heaving shows negligibly small effect on primary side power or temperature during normal operations.

Comparing with the results of JAERI analysis with 100% power operation in Fig. 4(b), the magnitude of oscillations of our results are smaller. The reason of this differences is that they revised the MUTSU S/G model, especially S/G height, slip model, and flow resistance, by comparing with the measured data at the MUTSU power-rising test and the experiment in the experimental voyages. Dotted line in Fig. 4(b) shows the results of the design analysis calculated by their simple model without the modifications of slip model or flow resistance. Therefore, our results are closer to the results of design analysis than RETRAN-02/GRAV calculation because we did not modified the slip model or flow resistance in RETRAN-03 code.

3.1.2. Effects of Stationary Inclination

To investigate the thermal-hydraulic behaviors of inclined reactors which is a familiar status as turning of ships, this study makes initially vertical reactor linearly incline to 30 degrees and retain that angle for a

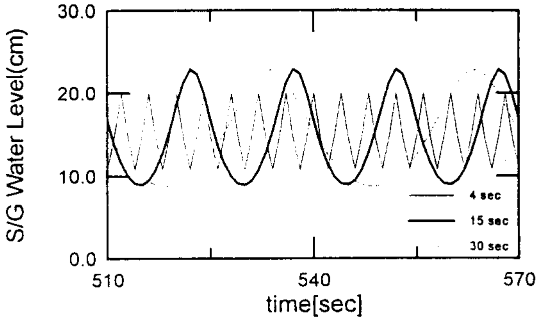


Fig. 4(a). S/G Secondary Side Behavior Under Heaving During Normal Operation

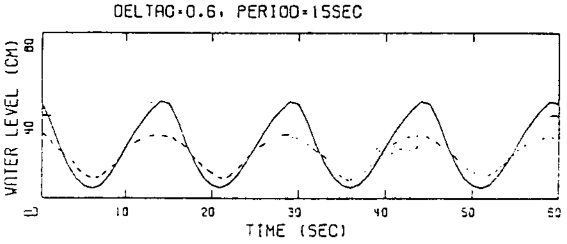
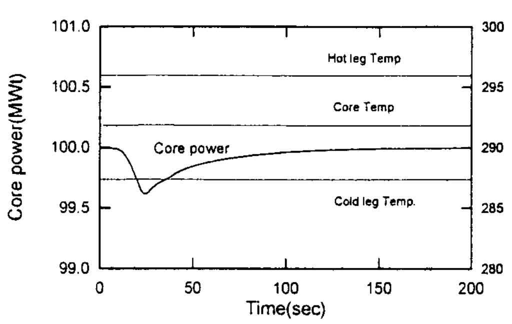
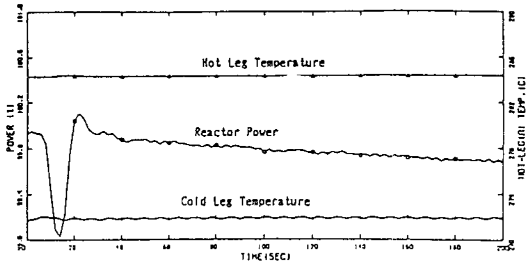


Fig. 4(b). Results of JAERI Analysis Under Heaving During Normal Operation (Period=15 sec, —RETRAN-02 Results ······Design Analysis)



(a) Results of RETRAN-03/MOV



(b) Results of JAERI analysis

Fig. 5. Effects of Stationary Inclination During Normal Poeration

long time. As shown in Fig. 5(a), reactor power slightly decreases at 15 sec and returns to its initial value about 100 sec. Core, hot leg, and cold leg temperatures increase very slightly and return to their initial values after the inclination. Comparing Fig. 5(a) and (b), there is a difference in cold leg temperature. In JAERI analysis, cold leg temperature oscillates with a very small amplitude but ours does not. The reason of difference is not clear. However, the difference of temperature and pressure change in the S/G secondary side between two calculations probably cause the difference. And it seems that the rapid power decrease at the beginning of inclination is caused by the change in moderator temperature coefficient induced by the slight temperature variation which is caused by the S/G secondary side recirculation flow rate change and the pressure change in the S/G evaporator during the inclination.

3.1.3. Effects of Rolling

Fig. 6(a) shows the results of rolling test. Rolling period is set to 15 seconds and rolling angles are 5, 10, 30 degrees. Results show that, with the larger rolling angle, the magnitudes of oscillations become larger. The magnitudes of S/G water level and recirculation flow oscillations are very small compared with the results of heaving as mentioned in chapter 3.1.1. Comparing with the results of JAERI analysis in Fig. 6(b), there are differences in the magnitudes of the S/G water level oscillations. These differences are caused by different slip models or input conditions of S/G feed water flow rate in two analyses because the slip models and geometries are modified for the larger value of oscillations in RETRAN-02/GRAV analysis. Further studies must be accomplished on this S/G secondary side behavior.

3.2. Natural Circulation

For the natural circulation state, the reactor is tripped at 30 seconds and the main coolant pump are tripped at 75 seconds.

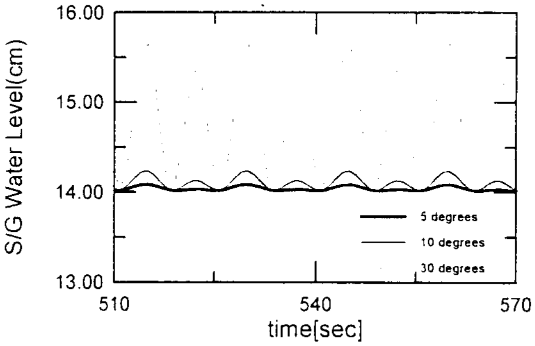


Fig. 6(a). S/G Secondary Side Behavior Under Rolling During Normal Operation

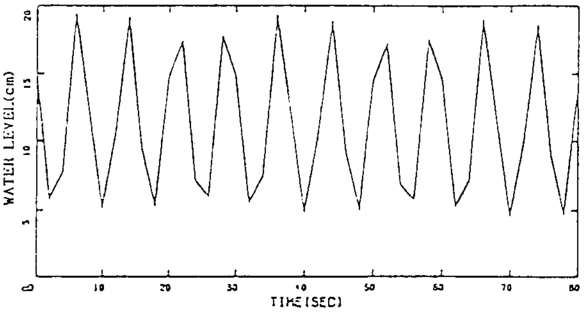


Fig. 6(b). Results of JAERI Analysis Under Rolling During Normal Operation (30 Degrees, 15 Sec.)

3.2.1. Effects of Heaving

Test conditions for heaving are same as explained in the case of normal operation. Results are shown in Fig. 7 with the periods of 4, 15, 30 sec. As in normal operation, loop flow rates oscillate with the gravity oscillation. As the oscillation period becomes larger, magnitudes of flow rate oscillations also become larger. Core flow rate are same as the sum of the loop 1 and loop 2 flow rates. For both normal operation and natural circulation state, it can be said that the reactor system parameters such as S/G water level and loop flow rates are varing with larger magnitudes as the heaving period increases. Hot and Cold leg temperatures are remained almost constant for all heaving periods.

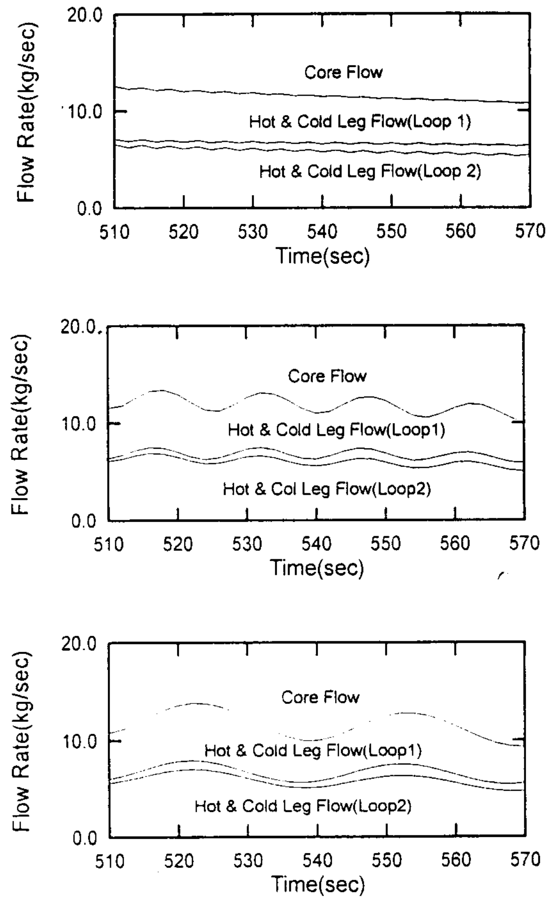


Fig. 7. Effects of Heaving During Natural Circulation

3.2.2. Effects of Stationary Inclination

Effects of inclination during natural circulation are shown in Fig. 8. Hot and cold leg temperatures are almost same as the results of without ship motion. Loop flow rates in hot and cold legs are changed after inclination. The loop flow rate of ascending loop(Loop 1) increased to the value of 9 kg/sec and that of descending loop is decreased to almost zero. Therefore after the inclination, the core flow rate is almost same as that of loop 1.

3.2.3. Effects of Rolling

To study the effects of rolling on the decay heat removal during natural circulation, the analysis of rolling for 30 degrees of rolling angle and 15 seconds of rolling period is performed. The loop flow rates oscillate with the same period of rolling and each loop has opposite trend in flow rate oscillation as shown in Fig. 9(a). In other words, as the flow rate in loop 1 increases, that in loop 2 decreases. The oscillation in core flow rate is caused by the phase difference in two loops. The phase lag of loop flows is considered to come from the geometrical asymmetry

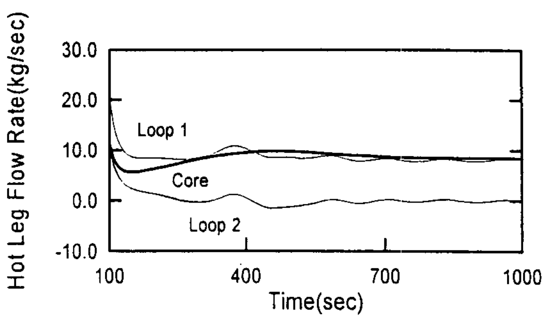


Fig. 8. Effects of Stationary Inclination During Natural Circulation

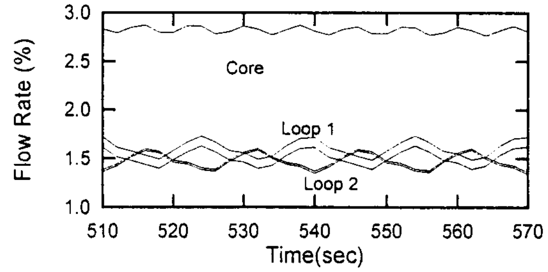


Fig. 9(a). Effects of Rolling During Natural Rirculation

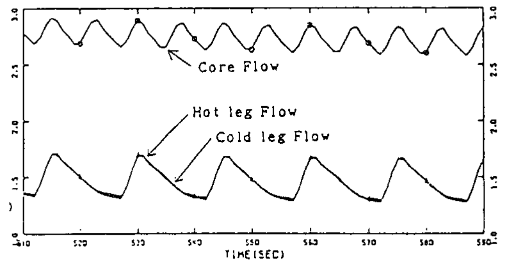


Fig. 9(b). Results of JAERI Analysis Under Rolling During Natural Circulation because the one loop has the pressurizer. And the insurge flow from the pressurizer causes the phase lag between two loops during the rolling motion. Core flow rate oscillates with the half of rolling period and its magnitude is small compared with those of loop flow rate oscillations. Temperatures of hot and cold legs also do not oscillate as in the case of heaving. It is concluded that primary side temperatures are not affected by ship motions such as heaving and rolling.

Comparing with the results of JAERI analysis in Fig. 9(b), core and loop flow rates shows good agreement both in magnitude and oscillation period.

4. Conclusions

RETRAN-03 code are improved for the analysis of thermal-hydraulics of ship reactors under various ship motions as well as natural circulation condition. Motions considered in the analysis are heaving, stationary inclination and rolling under normal operation and natural circulation conditions. The oscillations of S/G water level and recirculation flow mainly occur by vertical movement and their amplitudes of oscillations become larger with the larger oscillation period. For the 30 degrees stationary inclination under natural circulation, the loop flow in ascending loop can mostly represent the core flow because that of descending loop is negligibly small. In case of rolling, magnitudes of flow rate oscillations become larger with the larger rolling angle. Oscillations of two loop flow rates show opposite trend with some phase lag and thus the core flow rate also oscillates with smaller amplitude than that of loop flow rate oscillation.

Comparing with the results of the JAERI analysis, there are some differences in the magnitudes of S/G water level oscillations under heaving and rolling motion at normal operation. However, the trends and quantities of most variables show good agreements and typical thermal-hydraulic characteristics of marine reactors such as flow rate oscillations and S/G water level oscillations are successfully simulated. And it is concluded that even under the various ship motions, reactor system maintains stable thermal-hydraulic conditions for both normal operation and natural circulation states.

For the verification of the 3-D models developed in this study, experimental study for stationary inclination and rolling motion must be accomplished. Also, because the slip models and two phase heat transfer coefficients are developed under the stationary conditions, those models under inclination and rolling motion should be developed by both analytical and experimental studies in the future.

Nomenclature

A_k = flow area of volume k
BOT_k = length of the volume k in x-direction
F_w = friction force in 1/2(V_k) over length 1/2 (L_k)
$(\Delta p)_p$ = pressure drop associated with flow past a moving surface such as a pump
f_x, f_z = acceleration in x, z-direction
g_z = gravity
$g(t)$ = time dependent gravitation acceleration
L_k = height of volume k
R_x, R_y, R_z = distance between center of volume and center of rotation in x,y,z-direction
W_i = mass flow for junction i
Z = junction height above reference height z
Z' = junction height above reference height z after the rotation
Z_k = center of volume height above reference height z
Z_k' = center of volume height above reference height z after the rotation
$\overline{\rho_i}$ = average density in volume i

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