Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Influence of Rolling Motion on the Subchannel Analysis of Two-Phase Flows

Dae-Hyun Hwang*, Seong-Jin Kim
SMART Reactor Development Division, Korea Atomic Energy Research Institute
989-111 Daedeok-daero, Yuseong, Daejeon, 34057, Korea
**Corresponding author: dhhwang@kaeri.re.kr*

1. Introduction

Integral-type water-cooled SMRs is a promising candidate for ship applications, since they can readily fulfill the basic requirements of ship reactors such as compactness, lightness, reliability, and passive safety. Under the ocean conditions, the additional forces caused by three-dimensional movements of the reactor system may influence the thermal hydraulic fields of a reactor core as well as the thermal limits such as CHF phenomena. For evaluating the thermal power capability of a CHF-limiting SMR core, it is important to improve the prediction accuracy of CHF in subchannel levels.

Considering the possible movements of the reactor under ocean conditions, the influence of rolling motion on the subchannel analysis is investigated in this study. Additional forces generated in the rolling system change the gravitational losses in the subchannels. In addition, the buoyancy drift phenomena in the inclined subchannels may induce the energy transfer between neighboring subchannels at two-phase flow conditions. The subchannel analysis code MATRA was modified to examine the influence of one-dimensional rolling motions on the subchannel analysis of two-phase flows.

2. Model Description

2.1 Subchannel Analysis Models for Rolling Condition

The momentum equations in the non-inertial coordinate system need to consider the additional forces generated by the rotational movements. The additional acceleration terms under rolling motions can be expressed as [1]

$$\vec{a}_{add} = -2(\vec{\omega} \times \vec{V}) - (d\vec{\omega}/dt) \times \vec{r} - \vec{\omega} \times (\vec{\omega} \times \vec{r}) \quad (1)$$

, where the terms in the R.H.S. of eq. (1) represents the Coriolis, the tangential, and the centrifugal accelerations, respectively. The additional acceleration is reflected in the gravitational loss terms of the axial and lateral momentum equations. At a certain rolling condition with an inclination angle of θ, the subchannel axial and lateral momentum equations can be expressed as,

$$\frac{\partial}{\partial t}\dot{m}_i + \frac{\partial}{\partial z}\left(\frac{\dot{m}_i^2}{\rho' A_i}\right) + \sum_j W_{ij} u^* + f_T \sum_j w'_{ij} \Delta u_{ij} = -\bar{A}\frac{\partial}{\partial z}P - F_{f,z} - A_i \rho_i g_{eff} cos\theta \quad (2)$$

$$\frac{\partial}{\partial t}W_{ij} + \frac{\partial}{\partial z}\left(W_{ij}u_{ij}^*\right) = \frac{s}{l}\Delta P_{ij} - F_{f,ij} - s\rho_i g_{eff} sin\theta \cos\beta_{ij} \quad (3)$$

, respectively, where $F_{f,z}$ and $F_{f,ij}$ represent the axial and lateral friction losses, and β_{ij} is the angle between the lateral gravity and the W_{ji} direction perpendicular to the gap. The effective gravity is defined as $g_{eff} \equiv g - a_{add,z}$, where $a_{add,z}$ means the vertical-upward component of the additional acceleration.

The energy transfer due to gravity-induced vapor movement was considered in the mixture energy equation as

$$\frac{\partial(A\rho h)_i}{\partial t} + \frac{\partial(AGh)_i}{\partial x} + \sum_j W_{ij} h = Q - s\alpha^* \rho_g^* V_{r,ij} h_{fg} \quad (4)$$

, where the source term Q implies heat addition due to external heat source, fluid heat conduction, and turbulent mixing between adjacent channels. The last term in the R.H.S. of eq. (4) represents energy transfer due to the buoyancy drift, and * means the donor channel properties. It was assumed that the buoyancy drift does not cause a net mass transfer between subchannels. Referring to the previous work [2], the bubble rise velocity from channel *i* to *j* was expressed as,

$$V_{r,ij} = 1.5 \cdot \mathrm{F} \cdot \alpha^{0.1} \left[\frac{\Delta\rho\sigma g_{eff}}{\rho_l^2}\right]^{0.25} |\sin\theta| \cos(\beta_{ij}) \quad (5)$$

2.2 Additional Forces under One-dimensional Rolling Motion

One-dimensional rolling model was applied to the reactor core which has a symmetric configuration of geometry and one-dimensional characteristics of fluid flow. In the upward flow system with the rolling axis located at the upper part from the channel, the rolling angle and the angular velocity can be expressed as,

$$\theta(t) = \theta_m \cdot sin(2\pi t/T) \quad (6)$$

$$\omega(t) = 2\pi\theta_m/T \cdot cos(2\pi t/T) \quad (7)$$

, respectively. For the one-dimensional rotation as shown in Fig. 1, the vertical component of centrifugal acceleration directed toward the gravity acceleration. On the other hand, the vertical component of tangential acceleration acts in the upward direction which reduces the gravity acceleration. The effective gravity for the one-dimensional rolling motion can be expressed as

$$g_{eff}(\mathrm{t}) = g + 2\omega(t)\cdot u\cdot sin\theta(t) + \dot{\omega}(t)\cdot R\cdot sin\theta(t) + [\omega(t)]^2\cdot \mathrm{R}\cdot cos\theta(t) \quad (8)$$

As expressed in eqs. (6)~(8), the additional forces at any elapsed time (t) were affected by the rolling amplitude (θ_m), period(T), distance from the rolling axis (R), and fluid velocity (u).

For the rolling motions applied to this investigation ($\theta_m = \pi/4$, $T = 5\ sec$, $R = 1\ m$), the variation of additional acceleration terms with respect to the elapsed time during the rolling period is shown in Fig. 2. The Coriolis acceleration term was neglected in this study because it is relatively insignificant under gravity-dominant conditions. For the selected rolling motion, the effective gravity varied within $0.91\,g$ ~ $1.10\,g$. The minimum value of g_{eff} was determined by the tangential acceleration, while the maximum was determined by the centrifugal acceleration.

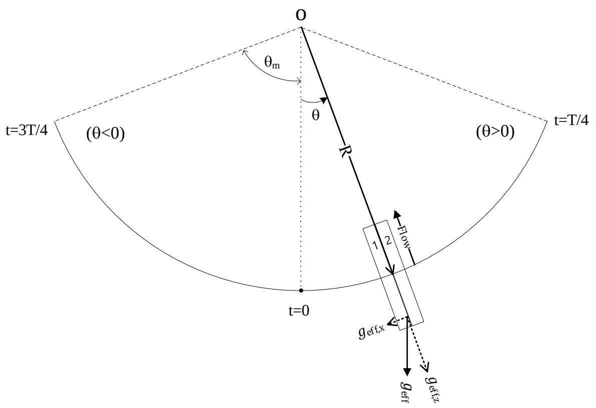

Fig. 1. Parameters for one-dimensional rolling motion

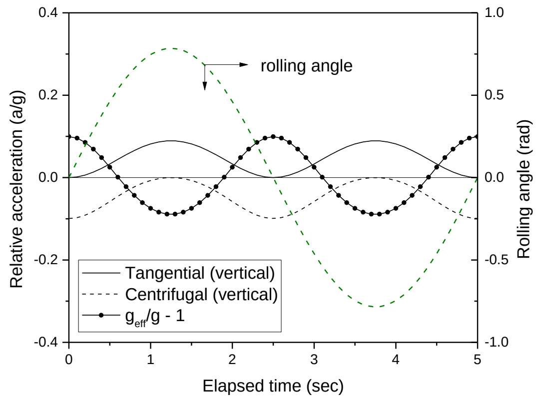

Fig. 2. Additional accelerations for one-dimensional rolling motions

3. Analysis Results

The influence of rolling motion is examined for two-channel sample problems. The rolling motion could affect the subchannel thermal-hydraulic conditions through the channel inclination effect and the additional forces acting on the gravitational losses. The effective gravity had its minimum value at the maximum channel inclination. The two-channel sample problem consisted of two geometrically identical channels. Major parameters for the analysis were channel hydraulic diameter of 15.6 mm, heated length of 1 m, gap size of 4 mm, gap angle (β_{12}) of 0 degree, system pressure of 10 MPa, channel inlet coolant temperature of 270 deg-C, channel peaking factor of 1.0, and uniform axial power distribution.

During the rolling period, (i) the gravitational loss term in the lateral momentum equation, and (ii) the energy transfer by the buoyancy drift in the energy equation were regarded as important factors for determining the thermal hydraulic conditions of the two channels. As shown in Fig. 1, the channel-1 located under the channel-2 during the elapsed time of 0 ~ T/2 seconds. During this period, the crossflow by effect-(i) increased the mass flux of channel-1, while the effect-(ii) reduced the enthalpy (or void fraction) of channel-1 at the two-phase flow region.

3.1 Results for Friction-dominant Condition

The variations of channel flow rate and void fraction affected the frictional and gravitational losses for each subchannel. Under the high velocity conditions, the pressure difference between the neighboring channels, i.e. ΔP_{ij} in eq. (3), was governed by the frictional losses of the channels. At the single-phase or low void conditions, the lateral gravity effect prevailed the increase of axial pressure loss in channel-1 which resulted in the increased mass flux of channel-1. At higher void conditions, the mass flux in channel-1 increased further since the frictional losses in channel-2 was increased due to the two-phase friction multiplier effect. As the results of a quasi-steady analysis, the channel-1 mass flux had the maximum value at $\theta = \theta_m$ as shown in Fig. 3, mainly due to the effect of energy transfer by the buoyancy drift.

3.2 Results for Gravity-dominant Condition

Under the gravity-dominant low velocity conditions, the flow distribution in the two channels revealed different behavior as shown in Fig. 4. In the gravity-dominant condition, the ΔP_{ij} in the lateral momentum equation was determined by the gravitational losses at each channel. As the two-channel inclined due to the rolling motion, the lateral gravity effect induced a crossflow toward lower channel (channel-1). On the other hand, the energy transfer caused by the buoyancy drift reduced the void fraction at channel-1. The effect of increased gravitational losses at channel-1 overcame the lateral gravity effect. As the result, the channel-1 mass flux decreased at the first half of rolling period as shown in Fig. 4.

As the channel slope increased, the influence of gravitational losses in the channel pressure drop decreased which was attributed to the reduction of the effective gravity and the hydrostatic head. The higher frictional loss in channel-2 revealed a subsidence of the mass flux behavior near the maximum inclination conditions as shown in Fig. 4.

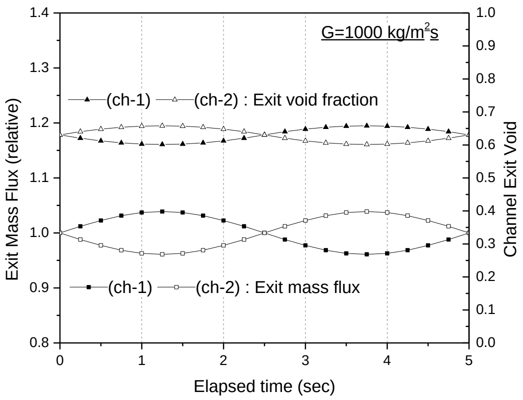

Fig. 3. Variation of subchannel mass flux and exit void during the rolling period under friction-dominant conditions

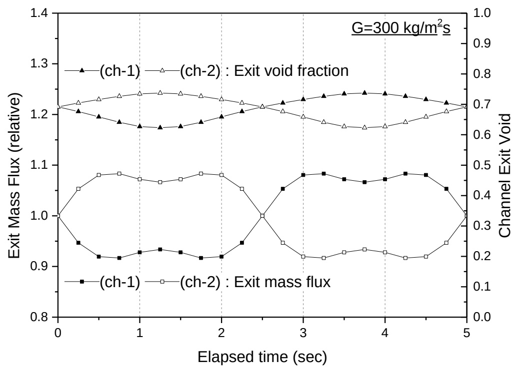

Fig. 4. Variation of subchannel mass flux and exit void during the rolling period under gravity-dominant conditions

4. Conclusions

The influence of rolling motions on the subchannel analysis of two-phase flows were examined by employing a subchannel analysis code MATRA. Additional forces caused by the rotational movements of the non-inertial coordinate system were incorporated into the axial and lateral momentum equations of the MATRA code. A constitutive model for simulating the energy transfer due to gravity-induced void drift was implemented in the energy conservation equation.

For a sample problem, the thermal-hydraulic characteristics of the two subchannels were investigated for one-dimensional rolling motions. The variation of effective gravity and the energy transfer by buoyancy drift influenced the subchannel mass fluxes and void fractions during oscillations. Different behavior of mass flux distribution was found for the friction-dominant and the gravity-dominant conditions. The variation of channel inclination angle revealed a mixed influence on the subchannel mass flux under gravity-dominant low velocity conditions.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korea Government (Ministry of Science and ICT) (NRF-2020M2D7A1079181).

REFERENCES

[1] F.M. White, Fluid Mechanics, 4th ed., Chapter 3, McGraw-Hill, 1999.
[2] D.H. Hwang, S.J. Kim, Influence of channel orientation on the subchannel analysis of two-phase flow, Trans. KNS Spring Mtg., paper 21S-107, May 13-14, 2021.