Numerical Simulation of Subcooled Boiling in Swing Rectangular Channel based on Non-Equilibrium Thermal Model

Le Liu [1, 2, a, *], Wenzhen Chen [1, b], Cong Wang [2], Jie Song [2], Xiaoxiao Wang [2]

[1] Navy University of Engineering, Wuhan 430033, China

[2] Wuhan Second Ship Design and Research Institute, Wuhan 430064, China

[a, *] Corresponding author e-mail: liulesky@foxmail.com, [b] Cwz2@21cn.com

Abstract. Theoretical analysis on the fluid flow in a vertical rectangular channel under swing motion is performed to establish the mathematical model which is based on Eulerian two-fluid framework and non-equilibrium subcooled boiling model. It is analyzed that the flow and heat transfer characteristics and the force of the fluid under the condition of forced flow and swing motion condition. The results show that, for the existence of Coriolis force, the period of acceleration of the fluid is 1/2 of the period of swing angle, and the phase differ. In the rectangular channel, the angle of pressure isoline and horizontal line is sinusoidal likely, which is behind the swing angle phase; Due to the influence of the periodic force field, with the increase of the swing angle, the bubbles in the rectangular channel move to one side, and the wall temperature also increases, which leads to the deterioration of heat transfer; In a swing period, the vapor volume fraction at the outlet and the pressure drop between the inlet and outlet of the rectangular channel fluctuate, and the vapor volume fraction is located at the minimum pressure drop, and the vapor volume fraction at the outlet fluctuates in a trough type.

Keywords: Non-equilibrium Thermal Model; Heat Transfer Characteristics; Numerical Simulation.

1. Introduction

As nuclear power plants are used in the oceans, people are beginning to explore the impact of marine environmental conditions on the safety of nuclear power plants. The rolling condition brings periodic additional force to the fluid flow and boiling heat transfer in the nuclear power plant, which leads to the deviation of the nuclear power plant from the nucleate boiling phenomenon and the large difference on land. Therefore, it is necessary to study the characteristics of critical heat flux in rolling motion.

In this work, the subcooled boiling phenomenon of cooling water and the flow and heat transfer characteristics of two-phase flow in a rectangular channel under rolling condition are numerically studied. The effects of rolling on the stress, vapor content, wall temperature, inlet and outlet pressure drop and other key parameters of the fluid in the rectangular channel are analyzed.

2. Mathematical Physics Model and Simulation Conditions

2.1 Physical Model

In order to analyze the effect of rolling motion on heat transfer, a rolling coordinate system is established as shown in Fig. 1 [1]. The non-inertial coordinate system o'x'y'z' fixed on the rectangular channel is used to study, while the inertial coordinate system oxyz is placed on the earth. In order to embody generality, the rolling axis is set as X axis, and the center of the vertical study section is 3 m above the origin o' of the non-inertial coordinate system. The absolute acceleration ($\vec{a}_a$) of an instantaneous point (x, y, z) is equal to the vector sum of the instantaneous implicated acceleration ($\vec{a}_e$), relative acceleration ($\vec{a}_r$), Coriolis acceleration ($\vec{a}_C$). The axial acceleration distribution is shown in Fig. 2. According to the D'alembert principle, the direction of inertia force acting on a particle is opposite to the direction of acceleration. The mass force acting on a unit mass includes gravity $\vec{g}_0$, normal inertia force $\vec{F}_n = -\vec{\omega} \times (\vec{\omega} \times \vec{r}')$, tangential inertia force $\vec{F}_t = -\vec{\varepsilon} \times \vec{r}'$ and Coriolis inertia force $\vec{F}_C = -2\vec{\omega} \times \vec{v}'$.

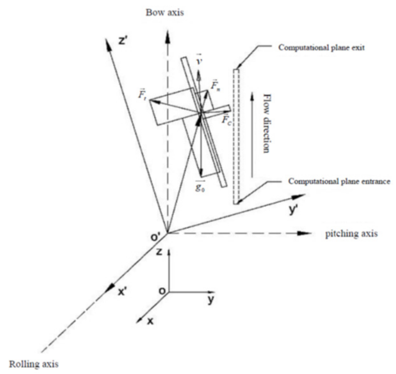


Fig 1. Schematic Diagram of Rolling Coordinate System

The sum of the additional inertia force and gravity components of an arbitrary mass point in the direction of flow is:

$$F_z = \rho\left(-g\cos\theta + a_t\cos\alpha + a_n\sin\alpha - 2\omega_e v_{rx}\right) \tag{1}$$

The sum of the normal upward components in the direction of flow is:

$$F_y = \rho\left(-g\sin\theta - a_t\sin\alpha + a_n\cos\alpha - 2\omega_e v_{ry}\right) \tag{2}$$

2.2 Mathematical Model

1). Two-phase Flow Model. The two-phase flow in subcooled boiling is described by using Euler-Euler two-fluid model. The mass, momentum and energy conservation equations for gas and liquid phases are established respectively. The momentum source term generated by rolling is introduced. Heat transfer, mass transfer and momentum exchange between two phases make the two-fluid model closed.

2). Subcooled Boiling and Critical Heat Flux Model. The subcooled boiling model adopts RPI boiling model proposed by Kurul and Podowski [2]. The model divides the wall heat flux into three parts: q_c liquid single-phase heat transfer, q_q intense cooling heat transfer and q_e vaporization latent heat. In order to calculate the three-heat flux, Tolubinski-Kostanchuk relation is introduced to calculate the bubble detachment diameter. Cole relation [3] calculates bubble detachment frequency, Lemmert and Chawla relation [4] calculates the vaporization core density, The Del Valle-Kenning relation [5] calculates the area specific gravity coefficient of the gas phase. In order to simulate the boiling phenomenon of bubbles with high void fraction near the wall, a non-equilibrium subcooled boiling model proposed by Lavieville was introduced, and a new heat flux term was introduced on the basis of RPI model. The model is as follows [6]:

$$q_w = f(\alpha_l)\left(q_c + q_q + q_e\right) + \left(1 - f(\alpha_l)\right)q_g \tag{3}$$

$$f(\alpha_l) = \begin{cases} 1 - \dfrac{1}{2}e^{-20(\alpha_1 - \alpha_{1,crit})} & \alpha_1 > \alpha_{1,crit} \\ \dfrac{1}{2}\left(\dfrac{\alpha_1}{\alpha_{1,crit}}\right)^{20\alpha_{1,crit}} & \alpha_1 \le \alpha_{1,crit} \end{cases} \tag{4}$$

Where: q_w is the wall heat flux, $f(\alpha_l)$ is the area proportion of liquid encapsulated area, q_c is the heat transfer of liquid in single phase, q_q is a convective heat transfer due to intense cooling, q_e is the latent heat of vaporization, q_g is the single-phase heat transfer in gas phase, α_1 is the volume fraction of liquid phase, for $\alpha_{1,crit} = 0.2$.

3. Calculation Model and Simulation Conditions

3.1 Calculation Model

The rectangular channel of the vertical research section is the fluid passage between the two heating plates. The width of the rectangular channel is 15.4 mm and the height of the heating section is 2 m. In order to eliminate the influence of the inlet and outlet on the heating section, the upper and lower ends of the heating section are respectively increased by 0.5 m. The exit section, as shown in Figure 2, has a simple geometry of the rectangular channel. The calculation area is a two-dimensional rectangular cross-section flow path, and the grid adopts a regular rectangular structured grid. The final grid number is 45000, which satisfies the calculation accuracy requirements.

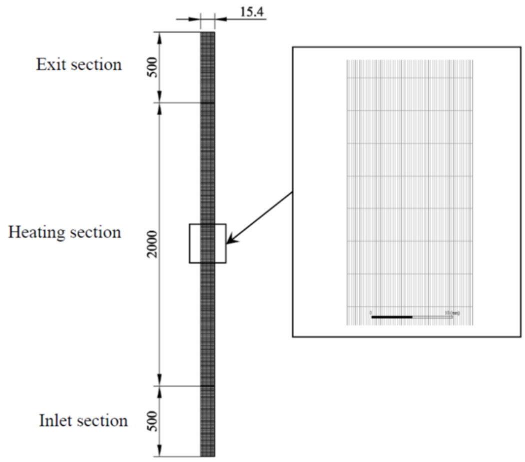


Fig 2. Calculation Model and Grid Diagram

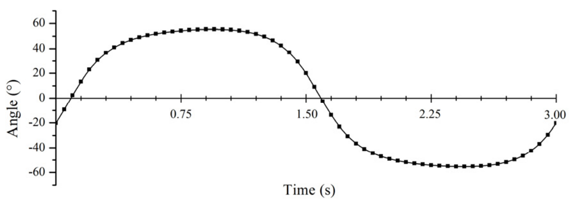
3.2 Simulation Conditions

The pressure of simulation conditions is 4.5MPa, The inlet temperature is 473.15K, The inlet mass flow rate is 900kg/(m^{2}s), The heat flux is 100-1400 kW/m^2, The rolling condition is rolling, the rolling amplitude is 30 degrees, the rolling period is 3s, and the rectangular channel is 1.5 meters above the centre of gravity of the platform.

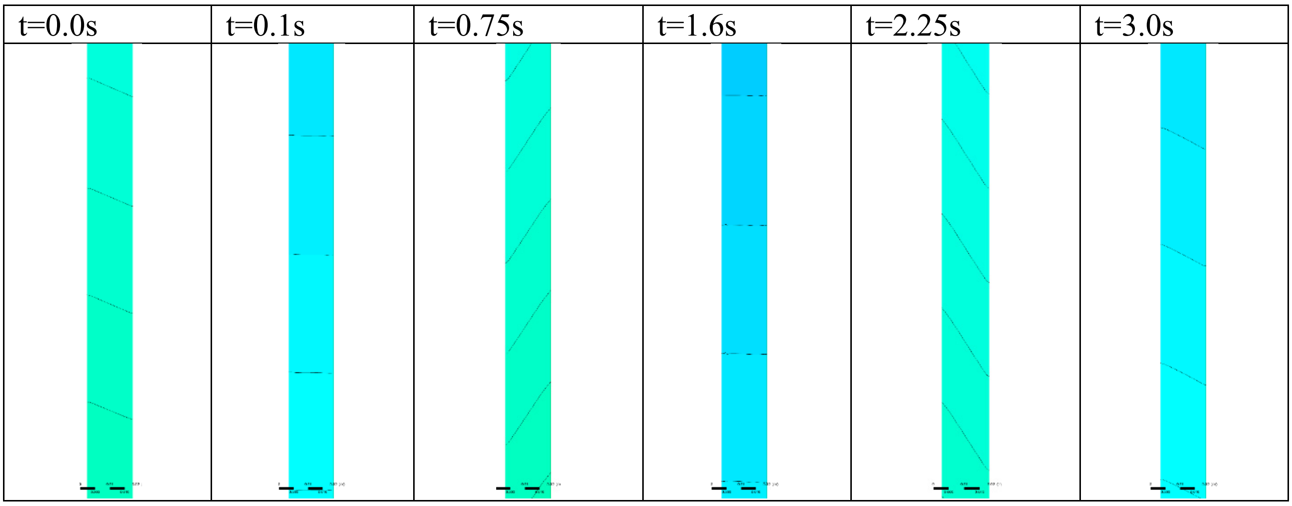
4. Calculation Results and Analysis

4.1 Effect of Rocking on Pressure

Fig. 3 shows the change diagram and curve of the angle between the direction of fluid pressure and the wall in a rectangular channel during a rolling period, It can be seen that due to the existence of inertial force, the change trend of the angle between the direction of fluid pressure and the wall surface is sinusoidal, which is obviously larger than the swing angle in the coordinate system, and the angle phase slightly lags behind the swing angle phase.



(a)



(b)

Fig 3. Angle between Pressure Direction and Wall

4.2 Effect of Swing on Steam Content

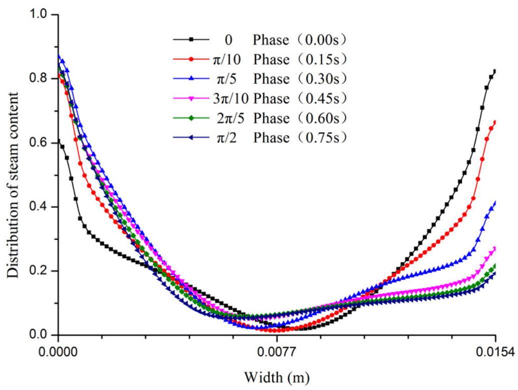


Fig 4. Distribution of Steam Content At Outlet Section with Time

Fig. 4 shows the change of the vapor content distribution of the exit section of the rectangular channel with time in the first quarter of the swing period. It can be seen that in the process of the swing angle from 0 to π / 2, the deviation of the vapor content at the two walls shows the same trend of change as the angle between the pressure direction and the wall in the rectangular channel. The reason for the above change is that the radial distribution characteristics of the vapor-liquid two-phase working medium are transported by swing. The influence of the periodic force field caused by the dynamic introduction makes the distribution of the vapor-liquid phase change periodically. In the process of the gradual inclination of the flow passage, the vapor phase in one side of the flow passage tends to be uniform due to the change of the pressure, the vapor content near the wall decreases, and the vapor phase in the other side gathers near the wall. Therefore, the degree of the uneven distribution of the vapor phase in the two walls varies with the fluid pressure and the direction The angle between the walls increases.

4.3 Effect of Rolling Motion on Temperature Distribution on Heating Wall

Figure 5 shows the variation of wall temperature with the rolling phase in vertical heating section with the wall heat flux of 900kW/m^2 under rolling motion. It can be seen that the wall temperature near the entrance is basically the same with the increase of the rolling phase. However, the wall temperature of the second half of the heating section increases rapidly with the increase of the rolling phase. It can be concluded that the rolling motion has little effect on the heat transfer around the entrance of the heating section. With the increase of the rolling phase, the wall temperature of the second half of the heating section increases and the heat transfer deteriorates. This is mainly due to the increase of the vapor content around the wall in the lower half of the section and the obvious influence of rolling conditions on the distribution of bubbles around the wall, which redistributes the bubbles in the rectangular channel, reduces the heat transfer capacity between the wall and the vapor-liquid phase, and increases the wall temperature.

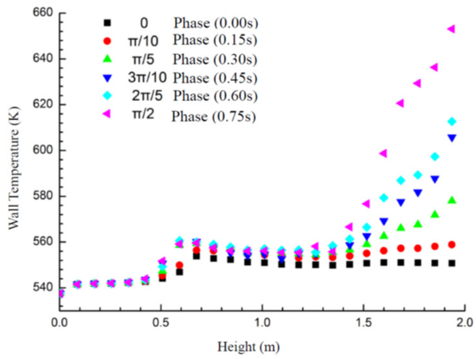


Fig 5. Wall Temperature Distribution under Rolling Motion

4.4 Effect of Swing on Outlet Steam Content

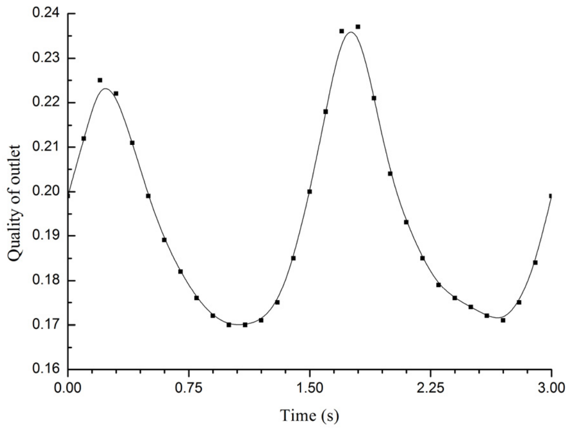


Fig 6. Thevapor Content At the Outlet in a Swing Period

Figure 6 shows the curve of the vapor content at the outlet of the rectangular channel in a swing period, In a swing period, there are two troughs of decreasing the vapor content at the outlet of rectangular channel, This is because the pressure fluctuation in the rectangular channel under swing condition causes the pressure fluctuation around the heating surface, which causes the steam liquid two-phase mixing on the boiling wall, so as to reduce the vapor content at the outlet of the rectangular channel, and the degree of its decline is related to the pressure fluctuation in the channel; however, the distribution of the vapor content in the rectangular channel is more uneven during rolling, which increases the vapor content around the single heating wall, And then it transits to the film boiling region, showing the trend of heat transfer deterioration.

5. Conclusion

Based on the non-equilibrium subcooled boiling model, the subcooled boiling phenomenon and the flow and heat transfer process of vapor-liquid flow in the rectangular channel under swing condition are numerically simulated.

(1) Based on the non-equilibrium subcooled boiling model, the phenomenon of subcooled boiling in a circular tube can be simulated more accurately.

(2) The rolling condition has no influence on the single-phase convective heat transfer, but has a great influence on the heat transfer in the nucleate boiling heat transfer zone. The two walls in the rectangular channel have the phenomenon of enhanced heat transfer and weakened heat transfer respectively. The maximum temperature of the inner wall during the rolling period appears at the phase point with the largest rolling angle;

(3) The rolling condition causes the pressure fluctuation in the rectangular channel to reduce the steam content at the outlet by two troughs in a rolling cycle, which makes the distribution of the steam content on the heating wall more uneven and the heat transfer deterioration trend appears.

References

[1] HUANG Zhen, GAO Puzhen, TAN Sichao, SHE Yingjuan. Mechanism analysis of effect of rolling motion on heat transfer. Nuclear Power Engineering, vol.31, no.3, pp.50-54, 2010(in Chinese).

[2] Kurul N, Podowski M Z. On the modeling of multidimensional effects in boiling channels. In Proceedings of the 27th National Heat Transfer Conference, Minneapolis, Minnesota, USA, pp.1-14, July. 1991.

[3] COLE R. A Photographic Study of Pool Boiling in the Region of the Critical Heat Flux. Aiche Journal, vol.6, no.4, pp.533-542, 1960.

[4] LEMMERT M, CHAWLA L M. Influence of flow velocity on surface boiling heat transfer coefficient in Heat Transfer in Boiling. New York: Academic Press and Hemisphere, 1977.

[5] Del Valle V H, Kenning D B R. Subcooled flow boiling at high heat flux. International Journal of Heat and Mass Transfer, vol.28, no.10, pp. 1907-1920, 1985.

[6] LAVIEVILLE J, QUEMERAIS E. MIMOUNI S. NEPTUNE CFD V1.0 Theory Manual. France: CEA/EDF, vol.28, no.10, pp. 1907-1920, 2005.