Numerical Simulation on Critical Heat Flux of Rectangular Channel in Rolling Motion

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Abstract. Theoretical analysis on the fluid flow in a vertical Rectangular channel under rolling motion is performed to establish the mathematical model which is based on Eulerian two-fluid framework and non-equilibrium subcooled boiling model. The numerical model is established to simulate the subcooled boiling. The trends of boiling curves under non-rolling motion condition, temperature of inner wall of rectangular channel and boiling curves under sinusoidal periodic rolling motion condition are essentially investigated. The results show that, it is suggested to treat the inflection point of boiling curves as the criterion of DNB which is marked by burnout point “q_{max}” under non-rolling motion condition. In a period of rolling motion, the max temperature of inner wall in vertical rectangular channel changes periodically under rolling motion condition, when the model deviates from the maximum equilibrium position, the maximum wall temperature appears. The burnout point “q_{max}” of boiling curves appeared earlier under rolling motion condition, after that the temperature rise faster than non-rolling motion condition.

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. Some numerical calculations and theoretical studies have been carried out on the flow and heat transfer in rectangular channels in rolling motion [1-3]. However, they are all based on the influence of rolling motion on the flow and heat transfer of single-phase fluids. There are few studies on the flow and heat transfer of two-phase fluids in rolling motion. With the development of numerical calculation technology, the researchers have done a lot of research on the numerical simulation of boiling and critical heat flux in the tube, and achieved certain results [4-5], At present, due to the development of marine and marine nuclear power, numerical simulation of critical heat flux in specific channels in rolling motion still needs further study.

In this work, the numerical analysis of the subcooled boiling and critical heat flux of two-phase flow fluid in a rectangular channel in rolling motion is compared with the results of critical heat flux in
non-rolling motion, and the influence of rolling motion on the heat transfer of two-phase fluid is analyzed.

2. Mathematical physics model and simulation conditions

2.1. Physical model

![Schematic diagram of rolling coordinate system](image)

**Figure 1.** Schematic diagram of rolling coordinate system

In order to analyze the effect of rolling motion on heat transfer, a rolling coordinate system is established as shown in Fig. 1 [3]. 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 ($\ddot{a}$) of an instantaneous point $(x, y, z)$ is equal to the vector sum of the instantaneous implicated acceleration ($\dot{a}$), relative acceleration ($\ddot{a}$), Coriolis acceleration ($\dot{C}$). 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 $g$, normal inertia force $F_n = -\vec{\omega} \times (\vec{\omega} \times \vec{r'})$, tangential inertia force $F_t = -\vec{e} \times \vec{r'}$ and Coriolis inertia force $F_C = -2\vec{\omega} \times \vec{v'}$.

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

$$F_z = \rho \left( -g \cos \theta + a_i \cos \alpha + a_e \sin \alpha - 2\omega \times v_n \right)$$  \hspace{1cm} (1)

The sum of the normal upward components in the direction of flow is:
$$F_y = \rho \left( -g \sin \theta - a \sin \alpha + a \cos \alpha - 2\omega \nu \right)$$  \hspace{1cm} (2)

Figure 2. Axial acceleration

Where:

$$\theta(t) = \theta_m \sin \left( \frac{2\pi}{T} t \right)$$  \hspace{1cm} (3)

$$\omega(t) = \frac{\theta_m}{T} \cos \left( \frac{2\pi}{T} t \right)$$  \hspace{1cm} (4)

$$\varepsilon(t) = -\theta_m \left( \frac{2\pi}{T} \right)^2 \sin \left( \frac{2\pi}{T} t \right)$$  \hspace{1cm} (5)

Where, $\theta(t)$ is the instantaneous rolling angle, $\omega(t)$ is instantaneous rolling angular velocity, $\varepsilon(t)$ is instantaneous rocking angular acceleration, $g_0$ is gravitational acceleration, $\theta_m$ is the maximum rolling angle, $T$ is the rolling frequency, $t$ is time.

2.2. Mathematical Model

2.2.1. 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.

2.2.2. Subcooled Boiling and Critical Heat Flux Model, The subcooled boiling model adopts RPI boiling model proposed by Kurul and Podowski [6]. 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 [8] calculates bubble detachment frequency, Lemmert and Chawla relation [9] calculates the vaporization core density, and The Del Valle-Kenning relation [10] 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 [11]:

\[
q_w = f(\alpha_l)(q_e + q_q + q_v) + (1 - f(\alpha_l))q_g
\]

(6)

\[
f(\alpha_l) = \begin{cases} 
1 - \frac{1}{2}e^{-20(\alpha_l - \alpha_{l,crit})} & \text{if } \alpha_l > \alpha_{l,crit} \\
\frac{1}{2} & \text{if } \alpha_l \leq \alpha_{l,crit}
\end{cases}
\]

(7)

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

2.2.3. Interphase Heat and Mass Transfer Model, The mass transfer between the subcooled boiling phases mainly includes: 1) vaporization of the wall subcooled boiling liquid phase into the gas phase; 2) vapor entering the subcooled liquid phase and condensation into the liquid phase.

The expressions of heat transfer between two phases are as follows:

\[
\dot{q} = q_{hl} + q_{vl} = h_{ij}(T_{sat} - T_l) + \frac{\alpha_v \rho_v C_{p,v}}{\delta t}(T_{sat} - T_v)
\]

(8)

Where: \(\dot{q}\) is the heat transfer rate between two phases, \(q_{hl}\) is the heat transfer rate between the liquid phase and the interface, \(q_{vl}\) is the heat transfer rate between the vapor phase and the interface, \(h_{ij}\) is a volume heat transfer coefficient which is calculated by Ranz-Marshall model [12][13], \(T_{sat}\) is the saturation temperature, \(T_l\) is the liquid phase temperature, \(T_v\) is the vapor phase temperature, \(\alpha_v\) is the vapor phase volume ratio, \(\rho_v\) is the density of vapor phase, \(C_{p,v}\) is the constant pressure specific heat capacity of the vapor phase, \(\delta t\) is a time scale, the default is 0.05 [11].

The mass transfer expression between the two phases is as follows:

\[
\dot{m} = m_e + m_v + m_{vl} = \frac{q_v}{h_{p,v} + C_{p,v} \Delta T_{sat}} + \frac{\dot{q}}{h_{p,v}}
\]

(9)

Where: \(\dot{m}\) is the quality conversion rate between two phases, \(m_e\) is the mass conversion rate between phase interface and liquid phase, \(m_{vl}\) is the mass conversion rate between the phase interface
and the vapor phase, \( h_{fv} \) is the latent heat of vaporization, \( \Delta T_{sub} \) is the subcooling of the liquid phase, \( C_{p,l} \) is the constant pressure specific heat capacity of the liquid phase.

### 2.2.4. Interphase momentum transfer model

Two-phase flow turbulence model using RNG \( k-\varepsilon \) model, Gas phase turbulence enhancement using the Sato model [14]. The momentum transfer between the two phases is mainly achieved by the drag force between the two phases and the virtual mass force, lift, turbulent dissipation force, and wall lubrication. There is relative motion between the two phases, and the interphase drag is calculated by the Ishii-Zuber model [15]. Since the virtual mass force is relatively small, the impact of virtual mass force is not considered for the time being. Since the liquid phase velocity has a certain gradient in the normal direction of the flow direction, the lift of the gas phase in the liquid phase flow field is calculated by the Tomiyama model [16]. The turbulent flow dissipation in the gas phase is calculated by the Lopez-de-Bertodano model [17]. Due to the liquid phase velocity gradient near the near wall surface, the pressure distribution around the liquid phase bubble near the wall is greatly different, causing the gas phase bubble to be pushed toward the centre of the flow channel. This force is described by the wall lubrication force, and the wall lubrication force is calculated by the Antal model [18].

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### 2.3. Model verification

Bartolomei [19] verified the unbalanced subcooled boiling model by experimental data of subcooled boiling in a vertically heated circular tube at a pressure of 4.5 MPa. The diameter of the round pipe is 15.4mm, the length of the heating section is 2m, the heat flux density is 570kW/m², the inlet mass flow rate is 900kg/ (m²s), and the inlet subcooling degree is 58.2K. And fully consider the impact of import and export on the calculation, the calculation results and test results are compared as shown in Figure 3. It can be seen from Fig. 3 that the numerical simulation results are in agreement with the experimental data well, and the unbalanced subcooled boiling model can simulate the phenomenon of subcooling boiling under forced convection conditions.
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 4, 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.

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/(m²s), The heat flux is 100-1400 kW/m², 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. Boiling Curve

The boiling curves in rectangular channels are shown in Fig. 5 under non-rolling conditions. It can be seen that with the increase of heat flux, the wall superheat $\Delta T_{\text{sup}}$ shows a piecewise linear trend. When the wall superheat ($\Delta T_{\text{sup}} < 0$), the area is convective heat transfer zone, and the wall temperature of single-phase heat transfer changes linearly with the heat flux density. When the wall superheat ($\Delta T_{\text{sup}} > 0$) reaches the next inflection point, the region is a nucleate boiling heat transfer zone. It can be seen that the increase of wall temperature in this region is smaller than that in the subcooled convective heat transfer region. The main reason is that subcooled boiling enhances the wall heat transfer and enhances the wall heat transfer coefficient. When the heat flux continues to increase, the wall temperature passes through an obvious inflection point. This area is a critical area, and the wall superheat increases sharply. It is because with the increase of heat flux, the bubbles converge and cover the heating surface, the steam removal process deteriorates, and the wall heat transfer coefficient decreases sharply. It can be judged that the inflection point has deviated. The heat flux at DNB is critical heat flux (CHF).

Fig. 6 shows the variation of wall temperature with the rolling phase in vertical heating section with the wall heat flux of 900kW/m² 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.
4.2. Effect of rolling motion on Temperature Distribution on Heating Wall

![Wall Temperature Distribution under rolling motion](image)

**Figure 6.** Wall Temperature Distribution under rolling motion

4.3. Effect of rolling on Maximum Wall Temperature Distribution

![Comparison of Maximum Wall Temperature under rolling and Non-rolling Conditions](image)

**Figure 7.** Comparison of Maximum Wall Temperature under rolling and Non-rolling Conditions

Figure 7 shows the wall heat flux of 900kW/m² under rolling condition. The maximum temperature distribution of two heating surfaces in a rectangular channel in a rolling period is compared with the maximum temperature of the wall under non-rolling condition. It can be seen that the wall temperature has a sinusoidal distribution in a rocking period, and there are deterioration and enhancement of heat transfer respectively. The heat transfer of the heating surface in the rolling direction is strengthened, and the maximum wall temperature is lower than that in the non-rolling condition. The maximum wall temperature of the heating surface of the rolling phase surface is obviously higher than that of the non-rolling condition, and the heat transfer of the heating surface deteriorates. The main reason is that, because the inertia force of liquid is larger, with the increase of rolling angle, the vapor phase gathers around the rolling phase surface in the process of rolling, which leads to a higher vapor content around the heating surface, which is not conducive to the heat transfer between the wall and the vapor-liquid
phase. In this direction, the wall temperature reaches its maximum at the maximum rolling angle. In the rolling direction, the vapor phase fluid around the wall is squeezed by liquid phase fluid, the vapor content around the heating surface decreases, the heat transfer ability between the wall and the fluid increases, and the wall temperature decreases slightly in the rolling direction.

4.4. Effect of rolling on Boiling Curve

Figure 8. Comparison of boiling curves under rolling and non-rolling conditions

Figure 8 shows a comparison of boiling curves under rolling and non-rolling conditions in a rectangular channel. It can be seen that when the wall temperature is lower than the saturation temperature, the superheat curve of the inner wall of the channel coincides with that of the non-rolling condition under the rolling condition. That is to say, under the forced convection with single phase or low void fraction, the rolling has no effect on the heat transfer in the rectangular channel. With the increase of heat flux, when the wall temperature is higher than the saturation temperature, the rolling condition has an obvious effect on the heat transfer in the channel. The inflection point of boiling curve appears earlier, which leads to the smaller critical heat flux under rolling condition than that under non-rolling condition, and the wall temperature rising rate after boiling curve passes through inflection point is faster than that under non-rolling condition. It can be concluded that under the forced flow condition, in rectangular channel heated by constant heat flux, the oscillation condition makes the deviation from nucleation boiling (DNB) occur ahead of time, reduces the critical heat flux, and Delta T rises faster after $q_{\text{max}}$ burnout point.

5. Conclusion

Based on the non-equilibrium subcooled boiling model, the subcooled boiling and critical heat flux in a rectangular channel under rolling condition were 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, and the boiling curve can be calculated, and the critical heat flux under non-rolling conditions can be predicted.

2. The rolling condition has no effect on the forced convection heat transfer in single phase or low void fraction, and has a great influence on the heat transfer in the saturated nucleate boiling heat transfer zone. There are two phenomena of heat transfer enhancement and heat transfer weakening in the rectangular channel, respectively. The maximum wall temperature in the rolling period appears at the phase point with the largest rolling angle.
3. The rolling condition makes the deviation from nucleation boiling (DNB) occur earlier in the rectangular channel, and reduces the critical heat flux.

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