Effect of rolling motion on heat transfer characteristics of narrow rectangular channel with high subcooled boiling

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Abstract. In this paper, the effects of vertical and rolling motion conditions on high subcooled boiling heat transfer in narrow rectangular channels of natural circulation system are investigated experimentally. To analyze the error of instantaneous heat transfer coefficient better, a calculation error method based on temperature difference is proposed. The results show that the error between the predicted heat transfer coefficient of Yan's formula and the experimental value is less than 30% under vertical and rolling motion conditions.

1. Introduction
Natural circulation is a cycle formed under the action of gravity field, which does not rely on external power but depends on the density difference of fluid in the system circuit. Since this circulation mode is not affected by human factors and does not need additional power source, it is considered to be a reliable circulating flow mode. In the marine environment, the floating nuclear power will affected by marine conditions, and produce heave, tilt, rolling motion, etc. [1-2]. The natural circulation capacity is affected by the effective height difference of the cold and heat source centers, and is easily affected by the movement of the system devices. Because the driving head is small and the ability to maintain the original state is weak, the flow rate and velocity of the system will change greatly under the influence of additional motion such as heave, tilt, rolling motion [1], and even the flow field will change, which will cause the flow resistance and heat transfer characteristics of components to change.

The experimental study of pendyala [3] shows that the flow rate change caused by undulating motion can enhance the heat transfer capacity of laminar flow region. In the turbulent region, this effect is small. Wang Chang et al. [4] carried out the research work on the influence of rolling motion on the single-phase heat transfer characteristics of rectangular channels under forced circulation conditions, and obtained different conclusions. The experimental results show that under the same thermal parameters, the time average heat transfer coefficient under rolling motion condition is almost the same as that under vertical condition. However, the heat transfer equation under vertical condition cannot be used to predict the instantaneous heat transfer coefficient under rolling motion condition. The theoretical research of Li shaodan et al. [5] shows that the heat transfer in the heating plate is a process of transient heat conduction, and the calculation method of inner wall temperature under steady state condition is no longer applicable. It is easy to know that the research on instantaneous heat transfer coefficient under rolling motion condition needs to be improved.

Chen Y. [6] and Wang C. [7] carried out experimental research on subcooled boiling heat transfer characteristics in narrow rectangular channels under the condition of swing pair forced circulation. The results show that if the flow rate does not fluctuate, the radial periodic force field has little effect...
on the subcooled boiling heat transfer characteristics. However, when the flow rate fluctuates, the subcooled boiling heat transfer characteristics under rolling motion condition are different from those under steady flow condition. Wei J. et al. [8] simulated the subcooled boiling flow and heat transfer process in narrow rectangular channel under rolling motion condition by using FLUENT software. The results show that the effect of the additional force generated by rolling motion on the bubble can be ignored, but the flow fluctuation caused by rolling motion will change the stress state of the bubble, and then affect the boiling heat transfer characteristics.

Based on the above results, it can be found that there are few studies on the effect of rolling motion conditions on the two-phase boiling heat transfer characteristics. The calculation formula of heat transfer characteristics under rolling motion condition is mainly obtained by fitting the experimental data. Therefore, the application range of the correlation formula is narrow, and there is no formula that can predict the heat transfer characteristics of typical channel under rolling motion condition in a wide range. The research on the influence mechanism of rolling motion on heat transfer characteristics is not perfect.

2. Introduction of experimental equipment

As shown in Fig. 1, the experimental equipment is mainly composed of a rolling platform, a main circulation loop, a secondary side circulation loop and a measuring system. The main circulation loop is installed on the rolling platform, and the main water supply pipeline on the secondary side is connected with the inlet and outlet of the secondary side of the condenser through a hose. When the rolling platform does the rolling motion, the main loop will do the rolling motion together with the platform.

![Fig. 1 Schematic diagram of experiment equipment](image)

In the experiment, the motion of the rolling platform is used to simulate the simple harmonic motion of the ship. The rolling amplitude, acceleration and angular acceleration of the rolling platform follow the following laws:

$$\theta(t) = \theta_m \sin(\frac{2\pi}{T} t)$$

(1)
\[ \omega(t) = \frac{d\theta}{dt} = \theta_m\frac{2\pi}{T} \cos\left(\frac{2\pi t}{T}\right) \]

\[ \beta(t) = \frac{d\omega(t)}{dt} = -\theta_m\left(\frac{2\pi}{T}\right)^2 \sin\left(\frac{2\pi t}{T}\right) \]

In these formulas, \( \theta(t) \) is the instantaneous angle, rad; \( \omega(t) \) is the instantaneous angular velocity, rad/s; \( \beta(t) \) is the instantaneous angular acceleration, rad/s\(^2\). \( \theta_m \) denotes the rolling amplitude, rad, \( T \) as the oscillation period, s; \( t \) is time, s. It should be noted that "rad" is used in all angular units when calculating with the above expression. However, in describing the case, to avoid the long list of converted into radian system of decimal bring unnecessary trouble, the unit of the rolling amplitude adopts °.

3. Data processing

3.1. Calculation method of heat transfer coefficient error

In order to further analyze the error of heat transfer coefficient between calculation and experiment, according to the definition formula (4) of heat transfer coefficient and the calculation formula of relative error, the formula (5) for determining the error of heat transfer coefficient based on temperature difference is obtained.

\[ q_T = \frac{q}{\Delta T} \]  

where \( q \) is the heat flux density, W/m\(^2\); \( h \) is the heat transfer coefficient, W/(m\(^2\)K); \( \Delta T \) is the heat transfer temperature difference, °C. When \( q_e \approx q_c \), then

\[ \Theta_h = \frac{h_c - h_e}{h_c} = \frac{q_c}{\Delta T_c} - \frac{q_e}{\Delta T_e} \approx \frac{\Delta T_c - \Delta T_e}{\Delta T_e} \]

where, \( \Theta_h \) is the error of the heat transfer coefficient; \( h_c \) and \( h_e \) are the heat transfer coefficient obtained by calculation and experiment respectively, W/(m\(^2\)K); \( \Delta T_c \) and \( \Delta T_e \) are the temperature difference between the inner wall and the fluid obtained by calculation and experiment, respectively, °C.

The calculated temperature fluctuation curve is highly consistent with the experimental value. It can be considered that the instantaneous heat flux in the calculation is close to the experimental value. Therefore, the formula (5) is suitable for analyzing the instantaneous heat transfer coefficient error. It can be replaced by the difference between the experimental and calculated outer wall temperatures. So, the maximum error of instantaneous heat transfer coefficient can be calculated by the following formula:

\[ \Theta_{h,\text{max}} = \frac{T_{e,\text{ow}} - T_{c,\text{ow}}}{\min(\Delta T_c)} \leq \frac{\Omega(T_{e,\text{ow}} - T_{c,\text{ow}})}{\min(\Delta T_c)} \]

where \( \Theta_{h,\text{max}} \) is the maximum error; \( T_{e,\text{ow}} \) and \( T_{c,\text{ow}} \) are the external wall temperatures obtained by experiment and calculation respectively, °C; \( \min() \) indicates the function of taking the minimum value. \( \Omega() \) represents the function with the largest absolute value.
3.2. Judgment method of test phenomenon

Figure 2 shows the bubble morphology observed near the outlet of the heating zone under different rolling motion experimental conditions. The bubbles mainly appear on the heating wall, and the bubble diameter is small, only sliding along the wall, without obvious bubble aggregation and separation phenomenon. At the same time, combined with the temperature of the fluid at the outlet of the experimental section, it can be determined that the bubble belongs to high deficit hot boiling condition.

![Fig. 2 Bubbles in the heated section under different rolling motion condition when T\textsubscript{in}=70\textdegree C](a) 5\degree10s (b) 10\degree10s (c) 15\degree10s

4. Result analysis

4.1. Two phase heat transfer characteristics of narrow rectangular channel under vertical condition

Reference [9] analyzed the ability of different correlations of subcooled boiling heat transfer calculation to predict the local heat transfer coefficient of subcooled boiling in narrow rectangular channels under vertical conditions. The results show that Yan formula [10] (equation (7)) has good performance, and the deviation between predicted value and experimental value is about 30%, as shown in Fig.3. Therefore, the formula is introduced into the program [11] to verify the accuracy of the prediction of heat transfer capacity under vertical conditions, so as to analyze the instantaneous heat transfer characteristics under rolling motion with the aid of the program. The comparison results are shown in Fig. 4. The results show that the maximum error between the calculated outer wall temperature and the experimental value is 3.2 \textdegree C, and the corresponding local heat transfer coefficient error is 18%, which can be enveloped by the maximum error of the formula in the literature. Therefore, it is considered that the model can also be used within the experimental range of this paper.

\[
h_{tw} = Fh_{fc} + Sh_{pb}
\]  
(7)

where

\[
h_{fc} = Nu_{fc} \left( \frac{\kappa_f}{d_c} \right)
\]  
(8)

\[
h_{pb} = 0.00122 \frac{\kappa_f^{0.79} c_{p,f}^{0.45} \rho_f^{0.49}}{\sigma^{0.5} \mu_f^{0.26} \bar{\nu}_{fg}^{0.24} \rho_g^{0.24}} \left( T_w - T_s \right)^{0.24} \left( p_{sw} - p_s \right)^{0.75}
\]  
(9)

\[
S = \frac{1}{1 + 2.53 \times 10^{-6} Re_{i}^{1.17}} \left( \frac{T_w - T_s}{T_w - T_i} \right)^{0.9}
\]  
(10)

\[
Re_{i} = \frac{Gd_w}{\mu_f}
\]  
(11)
where, $\kappa_f$ is the thermal conductivity of the liquid phase, $w/(m\cdot{^\circ}C)$; $\sigma$ is the surface tension, N/m; $T_w$, $T_r$ and $T_s$ are the wall temperature, fluid temperature and saturation temperature, respectively, in $^\circ$C. $p_{sw}$ and $p_s$ are saturation pressures corresponding to wall temperature and liquid temperature, Pa; $c_{p,f}$ is specific heat at constant pressure of liquid phase, kJ/(kg$\cdot$C); $\Delta h_f$ is latent heat of vaporization, kJ/kg.

Fig. 3 Comparison between calculated result of Yan correlation and experimental data

Fig. 4 Comparisons between calculated result of code and experimental data

4.2. Study on two phase transient heat transfer characteristics under rolling motion condition

Fig. 5 ~ Fig. 7 show the comparison results between the experimental and calculated values of the external wall temperature of the heating plate under different thermal parameters and rolling motion parameters. The average temperature difference of inner and outer wall temperature corresponding to $T_{in}=70^\circ$C and $T_{in}=80^\circ$C is 10.6$^\circ$C and 9.0$^\circ$C respectively. The results show that the calculated values are in good agreement with the experimental values in terms of trend and amplitude under different parameters. Among them, the maximum relative error of amplitude is about 20%, the maximum phase difference of peak value is 0.9 s, and the maximum phase difference of valley value is about 0.5 s. However, compared with the single-phase temperature fluctuation, the change trend of the calculated value is worse than the average temperature. Considering that the calculation error of subcooled boiling heat transfer formula under vertical condition is larger than that under single-phase condition, such error result is acceptable. In Table 1, the instantaneous heat transfer coefficient error and the average heat transfer coefficient error are obtained according to equations (5) and (6) for further analysis. The results show that the maximum error of instantaneous heat transfer coefficient and time average heat transfer coefficient is 28.5% and 26.6%, respectively, which is less than the maximum error of the formula. Therefore, if the maximum error of the formula is acceptable, the instantaneous heat transfer coefficient of two-phase subcooled boiling in vertical condition can be used to predict the instantaneous heat transfer coefficient under rolling motion.

Table 1 The error of cycle-averaged and transient coefficient of heat transfer

| Location x (m) | $T_{in}=70^\circ$C, 5°10s | $T_{in}=70^\circ$C, 15°10s | $T_{in}=80^\circ$C, 15°10s |
|---------------|-------------------------|-------------------------|-------------------------|
|               | $\Theta_h$, ave  | $\Theta_h$, max  | $\Theta_h$, ave  | $\Theta_h$, max  | $\Theta_h$, ave  | $\Theta_h$, max  |
| 0.225         | 6.7%                   | 7.9%                   | 4.4%                   | 5.0%                   | 13.0%                   | 14.2%                   |
| 0.275         | 9.9%                   | 10.4%                  | 9.0%                   | 10.1%                  | 16.7%                   | 17.6%                  |
| 0.325         | 8.3%                   | 8.9%                   | 8.5%                   | 9.4%                   | 15.1%                   | 17.2%                  |
| 0.375         | 21.1%                  | 22.0%                  | 18.9%                  | 20.7%                  | 18.6%                   | 20.7%                  |
| 0.425         | 25.2%                  | 26.0%                  | 20.1%                  | 21.1%                  | 26.6%                   | 28.5%                  |
| 0.525         | 20.9%                  | 21.6%                  | 18.3%                  | 20.3%                  | 23.1%                   | 25.1%                  |

5. Conclusion

This paper presents a method to calculate the error of instantaneous heat transfer coefficient based on temperature difference. Based on this, the influence of rolling motion on the heat transfer
characteristics of narrow rectangular channel in natural circulation system was analyzed. Yan's formula can be used to predict the transient heat transfer characteristics of narrow rectangular channel with high subcooled boiling under rolling condition.

![Fig. 5 Comparisons between experimental and calculated value under Tin=70°C and 5°10s condition](image1)

![Fig. 6 Comparisons between experimental and calculated value under Tin=70°C and 15°10s condition](image2)
Fig. 7 Comparisons between experimental and calculated value under Tin=80℃ and 15°10s condition

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References
[1] Gao, P., 1997b. Mathematical model of primary coolant in nuclear power plant influenced by ocean conditions. J. Harbin Eng. Univ. (in Chinese)
[2] Su, G., Zhang, J., Guo, Y., et al., 1996. Effects of ocean conditions upon the passive residual heat removal system (PRHRS) of ship reactor. Atom. Emerg. Technol.(in Chinese)
[3] Pendyala R, Jayanti S, Balakrishnan A R. Flow and pressure drop fluctuations in a vertical tube subject to low frequency oscillations[J]. Nuclear Engineering & Design, 2008,238(1):178-187.
[4] Wang C, Li X, Wang H, et al. Experimental study on friction and heat transfer characteristics of pulsating flow in rectangular channel under rolling motion[J]. Progress in Nuclear Energy, 2014, 71(71):73-81.
[5] Li S, Tan S, Yuan H. Theoretical study on temperature oscillation of a parallel-plate in pulsating flow condition[J]. International Journal of Heat & Mass Transfer, 2015, 81:28-32.
[6] Chen Y. Study on heat transfer characteristics of fluid in rectangular channel under rolling condition [D]. Harbin Engineering University, 2012.
[7] Wang C. Flow and heat transfer characteristics in rectangular channel under periodic force field [D]. Harbin Engineering University, 2013.
[8] Wei J, Pan L, Xu J, et al. Numerical simulation of subcooled flow boiling in vertical rectangular channel under additional inertial force [J]. Journal of Chemical Engineering, 2011, 62(5):1239-1245.
[9] Tian W. Heat transfer characteristics of natural circulation in rectangular channel under rolling motion condition [D]. Harbin Engineering University, 2017
[10] Yan J, Bi Q, Liu Z, et al. Subcooled flow boiling heat transfer of water in a circular tube under high heat fluxes and high mass fluxes[J]. Fusion Engineering & Design, 2015, 100:406-418.

[11] Yu S, Jia Z, Guo X et al. The study on frictional resistance characteristics of narrow rectangular channel under rolling motion and highly subcooled boiling conditions [C] International Conference on Nuclear Engineering. Proceedings, ICONE27, Ibaraki, Japan, 2019.