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Original Article

Program development and preliminary CHF characteristics analysis for natural circulation loop under moving condition

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A B S T R A C T

Critical heat flux (CHF) has traditionally been evaluated using look-up tables or empirical correlations for nuclear power plants. However, under complex moving condition, it is necessary to reconsider the CHF characteristics since the conventional CHF prediction methods would no longer be applicable. In this paper, the additional forces caused by motions have been added to the annular film dryout (AFD) mechanistic model to investigate the effect of moving condition on CHF. Moreover, a theoretical model of the natural circulation loop with additional forces is established to reflect the natural circulation characteristics of the loop system. By coupling the system loop with the AFD mechanistic model, a CHF prediction program called NACOM for natural circulation loop under moving condition is developed. The effects of three operating conditions, namely stationary, inclination and rolling, on the CHF of the loop are then analyzed. It can be clearly seen that the moving condition has an adverse effect on the CHF in the natural circulation system. For the calculation parameters in this paper, the CHF can be reduced by 25% compared with the static value, which indicates that it is important to consider the effects of moving condition to retain adequate safety margin in subsequent thermal-hydraulic designs.

1. Introduction

In recent years, floating nuclear power is receiving increasing attention, some countries have been pioneering the development and application of Ocean Nuclear Power Plants (ONPPs) [1]. Compared with land-based nuclear power plant, the floating nuclear power plant has the advantages of shorter construction period, simplified anti-seismic design measure and the ability to move to almost any coastal place [2]. A recent example is Russia's barge-mounted nuclear power plant called Akademik Lomonosov, which can provide electricity to remote areas [3].

In terms of the form of motion, the main difference between the land-based and barge-mounted system is that the latter is subjected to ship motions such as rolling, heaving and pitching owing to the inertial force caused by the sea waves [4]. The relative position of the components in barge-mounted equipment as well as the gravitational field will change periodically, which induces periodic flow fluctuations [5,6]. It has been shown that the effect of the ship motion on the forced circulation is insignificant, but the effect on the natural circulation is significant [7]. So far, a few experimental studies on the natural circulation characteristic under the motion conditions have been published by related scholars. MURATA et al. [8] performed a series of single-phase natural circulation tests in a model reactor with rolling motion. Kim et al. [9] conducted the single-phase natural circulation experiments using scaled test facilities of the System-integrated Modular Advanced Reactor (SMART) to study the typical flow characteristics with different inclination angles. In order to obtain the effects of rolling motion on natural circulation flow and heat transfer, Tan et al. [10] carried out a series of experiments with and without rolling motions in a simple natural circulation flow loop. Yan et al. [11] preformed several experiments to investigate the operational characteristics of passive residual heat removal system under rolling motion. Current experimental studies have found that the natural circulation flow rate would oscillate regularly under the moving conditions, which further affects the natural circulation characteristics of the loop. Based on these, some thermal-hydraulic analysis programs have also been developed on the basis of their static versions, including the RETRAN-based programs [12–14] and

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Nomenclature

A	channel cross-sectional area, (m^2)
c_p	specific heat, (kJ kg^{-1} K^{-1})
De	channel equivalent diameter, (m)
D_e	channel equivalent diameter, (m)
$E_{n(q)}$	entrainment mass flux, (kg m^{-2} s^{-1})
E_v	vaporization mass flux, (kg m^{-2} s^{-1})
f	volume force
F	additional force of moving condition
g	gravitational constant, (m s^{-2})
G	mass flux, (kg m^{-2} s^{-1})
h	specific enthalphy, (kJ kg^{-1})
h_{fg}	latent heat of vaporization, (kJ kg^{-1})
M	interface friction force, (N·m^{-3})
p	pressure, (Pa)
$P_{rw(q)}$	wetted (heated) perimeter, (m)
q	channel surface heat flux, (kW m^{-2})
t	time, (s)
T	temperature, (K); motion period, (s)
u	velocity, (m s^{-1})
V	volume, (m^3)
x	vapor quality
z	channel axial coordinate, (m)

Greek symbols

α	volumetric fraction
τ	time, (s)
θ	rotational angle, (rad)
ω	rotational angular velocity, (rad s^{-1})
β	rotational angular acceleration, (rad s^{-2})
ρ	density, (kg m^{-3})
σ	viscous stress term

Subscripts

CHF	critical heat flux
D	droplets
F	liquid film
G	gas (vapor)
L	liquid phase
w	wall

RELAP5-based programs [15–17].

Since the dryout-type critical heat flux (CHF) in annular two-phase flow is an important thermal criteria for nuclear reactor design, several approaches including the use of empirical correlation and mechanistic modeling have been adopted to predict the CHF. The liquid film analysis models, which are developed based on the comprehensive effects of vaporization of the liquid film, deposition and entrainment of droplets, have been shown to be capable of predicting the occurrence of dryout in flow boiling channels [18–22]. The simplest approach is to only consider mass conservation equation of the liquid film, and the liquid film mass flow rate is calculated from a first-order nonlinear differential equation [18,20]. In contrast, a more sophisticated approach is to give full consideration to the interaction of three fields (i.e. film, droplet and vapor core) in the annular flow region, which includes a full set of conservation equations (mass, momentum and energy conservation equations) solved for three fields separately together with a set of closure relationships [19,22]. The quantitative comparison between the dryout predictions of above models and experimental data indicates good agreement under normal conditions. However, in a natural circulation loop under moving conditions, the influence of flow oscillation caused by motions on the CHF is still not well predicted. Some studies have found that the CHF correlation obtained under stable flow conditions, such as Katto and Ohno [23], predicted significantly larger values compared with the experimental data under oscillatory flow condition [24].

Thus, the main purpose of this paper is to study the dryout-type CHF characteristics in natural circulation loop under moving condition. In our previous work, an annular film dryout (AFD) mechanistic model has been developed based on the mass and momentum conservation equations of three fields [22]. In this paper, the additional forces caused by motions have been added to the mechanistic model to investigate the effect of moving condition on CHF, at the same time, a theoretical model of the natural circulation loop with additional forces is established to reflect the natural circulation characteristics of the loop system. By coupling the system loop with the AFD mechanism model, a CHF prediction program for natural circulation system under moving condition is developed. Furthermore, the CHF characteristics in the heated channel under the normal natural circulation condition and the natural circulation under the typical rolling condition are analyzed.

2. Physical model

In order to investigate the CHF characteristics in the natural circulation loop under moving condition, a two-phase flow natural circulation loop model is established, including condenser, pressurizer, preheater, valve, heated channel and connected pipes, as shown in Fig. 1. Several assumptions need to be stated: (1) The three-field based annular film dryout (AFD) mechanistic model for CHF. (2) One-dimensional homogeneous flow model for two-phase flow. (3) Additional forces are introduced into the momentum equations for the consideration of moving condition.

2.1. Natural circulation loop

The one-dimensional homogeneous flow model is applied, and the conservation equations of the loop is as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial z}\left(\frac{W}{A}\right)=0 \quad (1)$$

Momentum conservation equation:

$$\frac{\partial}{\partial t}\left(\frac{W}{A}\right)+\frac{\partial}{\partial z}\left(\frac{W^2}{\rho A^2}\right)=-\frac{\partial p}{\partial z}-\frac{fW|W|}{2\rho DeA^2}+(\boldsymbol{F}+\rho\boldsymbol{f})\cdot\boldsymbol{n} \quad (2)$$

Energy conservation equation:

$$\rho\frac{\partial h}{\partial t}+\frac{W}{A}\frac{\partial h}{\partial z}=\frac{qP}{A} \quad (3)$$

where $\boldsymbol{F}$ is additional force vector; $\boldsymbol{f}$ is volume force vector; $\boldsymbol{n}$ is coordinate vector of fluid flow. The density ρ and the enthalpy h are related with the ones of the two phases respectively:

$$\rho=\alpha\rho_g+(1-\alpha)\rho_l,.\ h=xh_g+(1-x)h_l \quad (4)$$

And the same form for mass flux G:

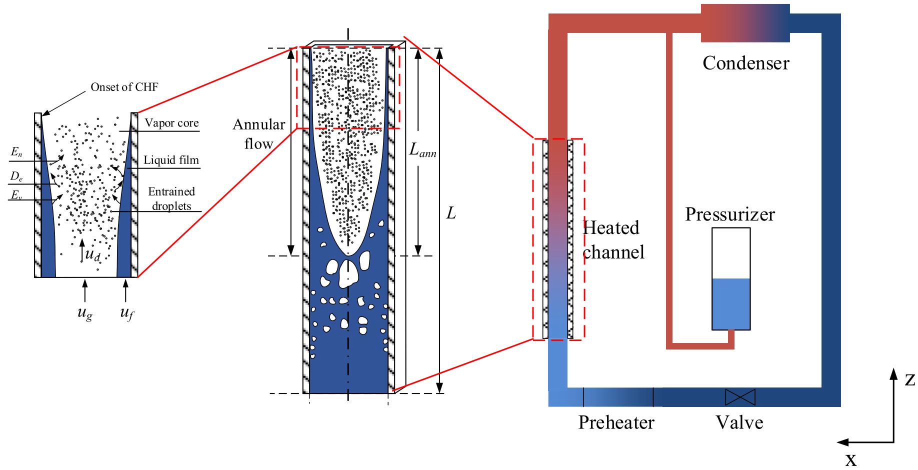


Fig. 1. Schematic of the natural circulation loop and CHF model.

$$G = \rho_l V_l (1-\alpha) + \rho_g V_g \alpha \tag{5}$$

In the heated channel, the axial heat conduction is ignored. Therefore, the heat is conducted only in the radial direction, which is given by:

$$mc_p \frac{dT_w}{dt} = Q - hA\left(T_w - T_f\right) \tag{6}$$

where m is the mass of wall material, c_p and h are heat capacity and surface heat transfer coefficient, respectively. Heat capacity is a function of wall temperature, and heat transfer coefficient is closely related to the local thermal hydraulic parameters, which can be determined by the corresponding correlation.

The double-pipe condenser is placed at the top of the circulation loop, which consists of heat transfer tube and shell side. The condenser pipe is divided into several control volumes in the axial direction, and each one includes fluid of primary and secondary sides. The enthalpy distribution in the condenser can be determined by solving the energy equations in each volume. The basic equations are:

$$\frac{dT_w(t)}{dt} = \frac{h_1 A_1 (T_1 - T_w) - h_2 A_2 (T_w - T_2)}{\rho_w V_w c_p} \tag{7}$$

$$\frac{dh_1}{dt} = \frac{W_1 (h_{1,in} - h_{2,ex}) - h_1 A_1 (T_1 - T_w)}{\rho_1 V_1} \tag{8}$$

$$\frac{dh_2}{dt} = \frac{W_2 (h_{2,in} - h_{2,ex}) + h_2 A_2 (T_w - T_2)}{\rho_2 V_2} \tag{9}$$

2.2. Critical heat flux

The CHF in the heated channel is based on the annular film dryout mechanistic model, whose typical characteristics is that the vapor core with entrained droplets flows in the center and the thin liquid film flows along the wall, and the CHF occurs when the thin liquid film is evaporated at outlet, as shown in Fig. 1. In our previous work [22], a three-field model has been developed based on the interaction between three fields in annular flow region, i.e. the liquid film, entrained droplets and vapor core. The fundamental conservation equations (Table 1) have been established together with a set of closure relationships.

Taking into account the additional forces under moving conditions, the new form of the momentum equations are as follows.

$$\begin{aligned} &\frac{\partial\left(\rho_f \alpha_f u_f\right)}{\partial \tau} + \frac{\partial\left(\rho_f \alpha_f u_f^2\right)}{\partial z} - \frac{D_{ep} P_{rw}}{A} u_d + \frac{q P_{rq}}{A h_{fg}} u_f + \frac{E_{nh} P_{rw} + E_{nq} P_{rq}}{A} u_f \\ &= -\alpha_f \frac{\partial p}{\partial z} + \alpha_f \left(\boldsymbol{F} + \rho_f \boldsymbol{f}\right) \cdot \boldsymbol{n} - M_{wf} + M_{fg} \end{aligned} \tag{10}$$

$$\begin{aligned} &\frac{\partial(\rho_d \alpha_d u_d)}{\partial \tau} + \frac{\partial\left(\rho_d \alpha_d u_d^2\right)}{\partial z} + \frac{D_{ep} P_{rw}}{A} u_d - \frac{E_{nh} P_{rw} + E_{nq} P_{rq}}{A} u_f \\ &= -\alpha_d \frac{\partial p}{\partial z} + \alpha_d (\boldsymbol{F} + \rho_d \boldsymbol{f}) \cdot \boldsymbol{n} + M_{gd} \end{aligned} \tag{11}$$

$$\begin{aligned} &\frac{\partial(\rho_g \alpha_g u_g)}{\partial \tau} + \frac{\partial\left(\rho_g \alpha_g u_g^2\right)}{\partial z} - \frac{q P_{rq}}{A h_{fg}} u_f = -\alpha_g \frac{\partial p}{\partial z} + \alpha_g \left(\boldsymbol{F} + \rho_g \boldsymbol{f}\right) \cdot \boldsymbol{n} - M_{fg} \\ &- M_{gd} \end{aligned} \tag{12}$$

where α and u represent the volume fraction and axial velocity at axial location z; P_{rq} and P_{rw} are the heated and wetted perimeters of the channel, respectively; A is channel cross-sectional area; D_e is the droplet deposition rate per unit area; E_{nh} and E_{nq} are the shearing entrainment rate and boiling entrainment rate per unit area, respectively.

In three-field model, the droplet entrainment and deposition correlations derived from Kataoka et al. [25] and Okawa et al. [26] have been adopted. In addition, the model mainly focuses on the flow oscillation and axial transport of liquid film caused by motion conditions. The change of velocity difference between vapor and liquid phase will affect the entrainment process of droplets, and other effects of interface waves are temporarily ignored.

2.3. Moving condition

When the flow is under moving conditions, the fluid will be in an additional acceleration field varying with time. Especially for the natural circulation system, the moving conditions will not only cause the fluid oscillation in the channel, but also change the gravity difference of the loop, which is important for the natural circulation ability. In general, the basic form of momentum

Table 1
The fundamental conservation equations of three-field model.

Mass continuity equations:

$$\frac{\partial}{\partial \tau}(\rho_f \alpha_f) + \frac{\partial(\rho_f \alpha_f u_f)}{\partial z} = -\frac{qP_{rq}}{Ah_{fg}} + \frac{P_{rw}D_e - (P_{rw}E_{nh} + P_{rq}E_{nq})}{A}$$

$$\frac{\partial}{\partial \tau}(\rho_d \alpha_d) + \frac{\partial(\rho_d \alpha_d u_d)}{\partial z} = -\frac{P_{rw}D_e - (P_{rw}E_{nh} + P_{rq}E_{nq})}{A}$$

$$\frac{\partial}{\partial \tau}(\rho_g \alpha_g) + \frac{\partial(\rho_g \alpha_g u_g)}{\partial z} = \frac{qP_{rq}}{Ah_{fg}}$$

Momentum conservation equation:

$$\frac{\partial(\rho_f \alpha_f u_f)}{\partial \tau} + \frac{\partial(\rho_f \alpha_f u_f^2)}{\partial z} - \frac{D_e P_{rw}}{A}u_d + \frac{qP_{rq}}{Ah_{fg}}u_f + \frac{E_{nh}P_{rw} + E_{nq}P_{rq}}{A}u_f = -\alpha_f \frac{\partial p}{\partial z} + \alpha_f \rho_f g - M_{wf} + M_{fg}$$

$$\frac{\partial(\rho_d \alpha_d u_d)}{\partial \tau} + \frac{\partial(\rho_d \alpha_d u_d^2)}{\partial z} + \frac{D_e P_{rw}}{A}u_d - \frac{E_{nh}P_{rw} + E_{nq}P_{rq}}{A}u_f = -\alpha_d \frac{\partial p}{\partial z} + \alpha_d \rho_d g + M_{gd}$$

$$\frac{\partial(\alpha_g \rho_g u_g)}{\partial \tau} + \frac{\partial(\alpha_g \rho_g u_g^2)}{\partial z} - \frac{qP_{rq}}{Ah_{fg}}u_f = -\alpha_g \frac{\partial p}{\partial z} + \alpha_g \rho_g g - M_{fg} - M_{gd}$$

Energy conservation equation:

$$\frac{dh}{dz} = \frac{qP_{rq}}{GA}$$

equation in the inertial frame is:

$$\rho\left(\frac{D\boldsymbol{u}}{Dt}\right) = -\nabla p + \sigma + \rho \boldsymbol{f} \tag{13}$$

Considering the motion conditions, an additional acceleration term is added to the momentum equation in the non-inertial frame:

$$\rho\left(\frac{D\boldsymbol{u}_r}{Dt}\right)_r = -\nabla p + \sigma + \rho \boldsymbol{f} + \boldsymbol{F} \tag{14}$$

Additional force $\boldsymbol{F}$ can be obtained by the acceleration synthesis theorem in the non-inertial frame, as shown in Fig. 2, which consists of four parts: translational acceleration, Coriolis acceleration, centripetal and tangential acceleration. The basic expression is as follows:

$$\boldsymbol{F} = -\rho\left[\boldsymbol{a}_0 + 2\omega \times \boldsymbol{u} + \omega \times (\omega \times \boldsymbol{r}) + \frac{d\omega}{dt} \times \boldsymbol{r}\right] \tag{15}$$

where $\boldsymbol{a}_0$ is the horizontal motion acceleration, ω is the angular velocity, $\boldsymbol{r}$ is the radius vector.

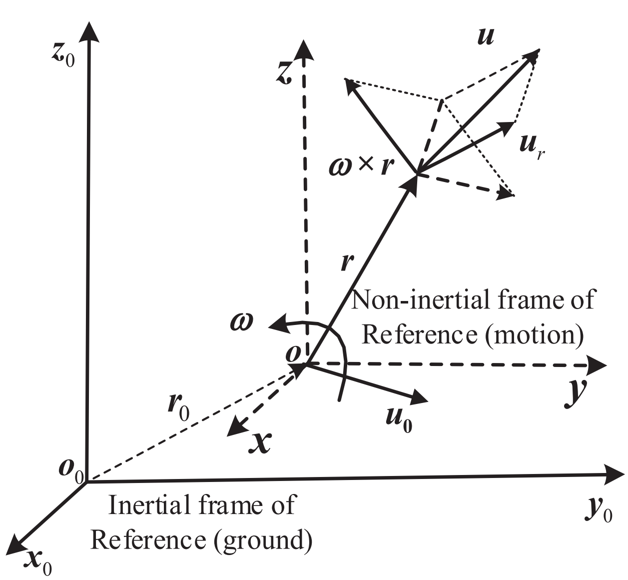


Fig. 2. Schematic of different coordinate frame.

2.4. Constitutive relation

To close the conservation equations described above, some other constitutive relations are required, such as the flow and heat transfer correlations, thermodynamic properties of water and steam. In the natural circulation loop, the flow relations mainly include single-phase friction pressure drop, two-phase friction multiplication factor, local resistance coefficient and void fraction relation. The main heat transfer processes include single-phase forced convection, nucleate boiling, transition boiling, film boiling and condensation heat transfer. Because the natural circulation flow rate is usually small, the heat transfer correlations can be divided into large flow rate area and small flow rate area. The relations selected in this study are listed in Table 2.

3. Program development and preliminary validation

Combining the above models, a computational program Called NACOM (Analysis program for the **CHF Of Na**tural circulation under **M**oving condition) is developed to calculate CHF in the natural circulation loop under moving conditions. For the natural circulation loop, the conservation equations are solved based on the SIMPLE algorithm, relevant parameters are shown in Table 3. The final form of solving the momentum equation, pressure equation and energy equation is the linear equations of each control volume node, and the cyclic tridiagonal matrix algorithm (TDMA) is applied. In addition, to give consideration to the calculation speed and convergence accuracy, the convergence value used is 10^{-3}. For CHF prediction, the mass flow rates of the liquid film, droplets and vapor core along the annular flow region can be calculated based on the evaporation (q/h_{fg}) of the liquid film, the entrainment (E_{nh} and E_{nq}) and deposition (D_{ep}) mechanism of the droplets. It is

Table 2
The flow and heat transfer correlations.

Description	Correlation
Void fraction	Chexal-Lellouche
Single phase friction pressure drop	Blasius
Two-phase friction multiplication factor	Martinelli
Single-phase forced convection	Dittus-Boelter
Nucleate boiling	Chen
Film boiling	Groeneveld
Transition boiling	Berenson
Condensation heat transfer	Chato
Property models	IAPWS-IF97

Table 3
Relevant parameters of numerical calculation method.

Description	Method
Discretization method	Finite volume method
Grid	One dimensional staggered grid
Convective term discretization	First-order upwind
Time term discretization	Fully implicit
Numerical algorithm	Transient SIMPLE
Algebraic equation solution	TDMA

considered that the dryout occurs when the void fraction of liquid film is less than 10^{-9}. A more specific description of the calculation process can be found in previous work [22]. For the relation between loop and CHF model, a domain-overlapping method is applied. The one-dimensional homogeneous model intends to model the entire loop while the three-field CHF model only simulates the heated section. At each transient step, the calculated values (i.e. inlet enthalpy and flow rate, outlet pressure) of the heated channel in loop will be transferred to the CHF model as the boundary conditions. Starting from the smaller heat flux q_m, it is judged whether the thin liquid film completely disappears at outlet of heated channel at each time step, and keep increasing q_m until CHF occurs. It should be noted that the increasing power in every step should be small enough to ensure the accuracy of CHF calculation. Fig. 3 shows the flow chart of the program calculation.

The natural circulation loop model and CHF model under transient condition in the developed program were validated separately. To validate the natural circulation loop model, a loop system corresponding to the experimental facility of Jain et al. [27] is established, which contains heated channels and condenser. The natural circulation gets established due to density difference between the heat source and sink. The loop was initially pressurized to 9 bar and heated from ambient conditions by gradually raising the channel power. Fig. 4 shows the comparison of the calculated loop flowrate with the experimental data for power from 32.4 kW to 51.8 kW, it can be seen that the calculated results of the loop flowrate has the same trend as the experimental values, and the relative error is less than 10%.

CHF validation under steady state has been done in the previous work [22]. And for transient condition, the experimental data of Zhao et al. [28] are compared, which were obtained in vertical tube with forced sinusoidal inlet flow oscillation. The oscillation period is 1–11 s, and normalized amplitude of inlet flow oscillation is 0–3.0. Fig. 5 describes the comparison between the calculated results of the model and the experimental results, where the solid data points represent experimental values, and the hollow ones are experimental values. It can be found that the calculated results have the same trend as the experimental results, except that the prediction accuracy of the model decreases slightly with the increase of the fluctuation amplitude.

4. Results and discussion

A simple natural circulation loop used for simulation is shown in Fig. 1. The length of the heated channel is 1500 mm, the total height of the circulation loop is 4800 mm, and the inner diameter of loop pipe is 20 mm. The parameter ranges are system pressure of 7–11 MPa, channel inlet subcooling of 0–180 °C and valve resistance coefficient of 0–1000.

4.1. The stationary condition

Based on the developed program, the CHF characteristics in the natural circulation system under stationary condition are first analyzed. As shown in Fig. 6, the transient change of mass flux and outlet equilibrium quality of heated channel are calculated with the power increasing in a ladder-typed way. The condition is under 8 MPa of system pressure and 60 °C of inlet subcooling of heated channel. It can be found that with the increase of power, the outlet equilibrium quality of the heated channel gradually increases. At the beginning, the natural circulation flow rate increases with the loop gravity head, and then starts to decrease with the further increase of the natural circulation resistance. Fig. 7 shows the judgment method of CHF in the loop, that is, dryout occurs when the

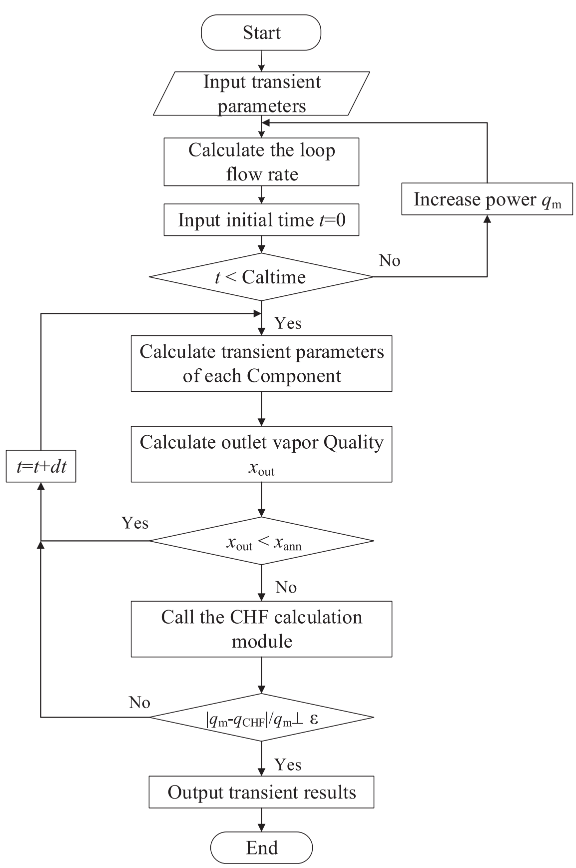


Fig. 3. The flow chart of transient calculation.

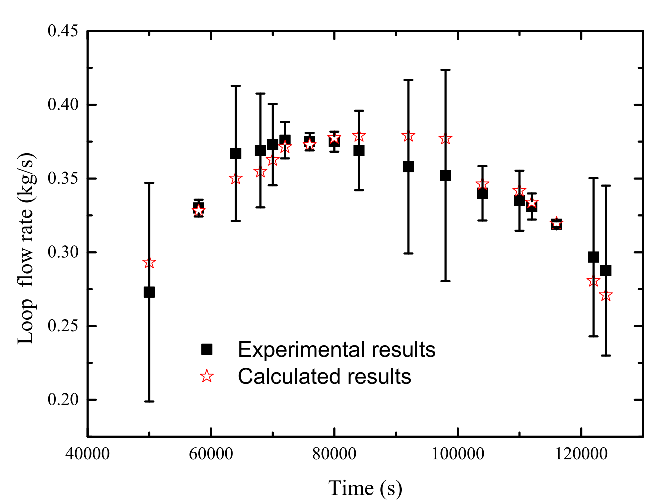
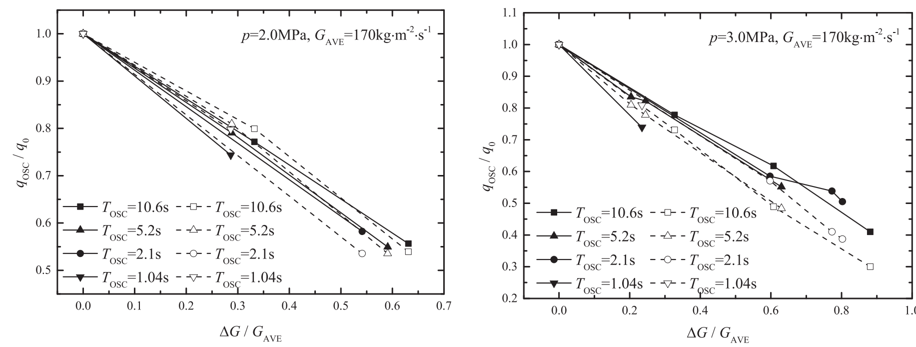


Fig. 4. The validation result of the circulation loop model.



(a) p = 2.0 Mpa (b) p = 3.0 MPa

Fig. 5. The validation results of CHF model under transient condition [29].

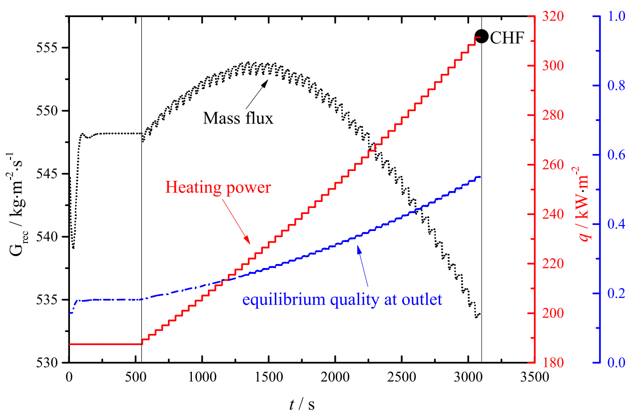


Fig. 6. Transient characteristics of flow and equilibrium quality under stationary condition.

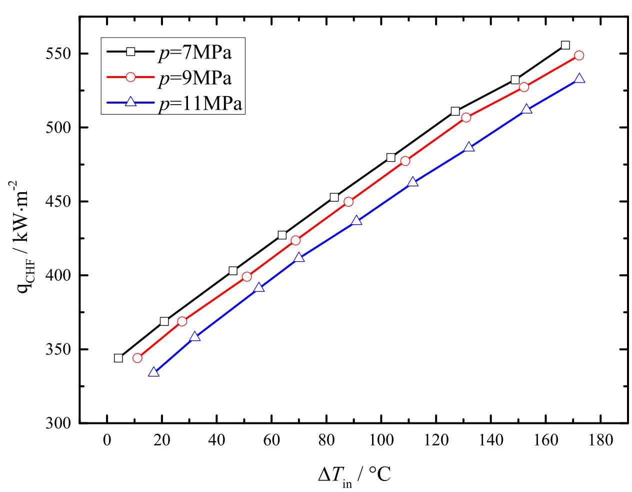


Fig. 8. The trend of CHF with system pressure and inlet subcooling.

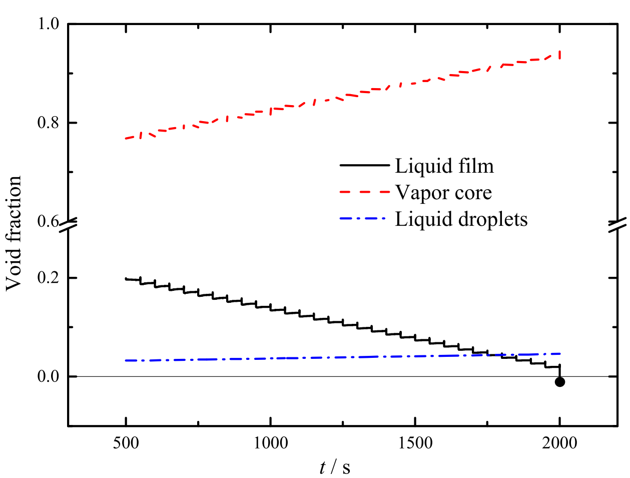


Fig. 7. The volume fraction of each phase at the outlet of the heated channel varies with time.

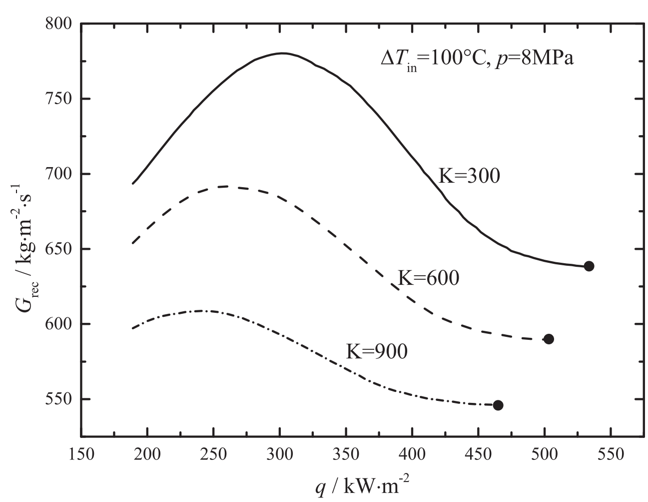


Fig. 9. The trend of CHF with valve resistance coefficient.

liquid film volume fraction at the outlet of the heated channel is exactly reduced to 0.

Figs. 8 and 9 show the trend of CHF in the natural circulation loop with system pressure, inlet subcooling of heated channel and valve resistance coefficient. As expected, the CHF increases almost linearly with inlet subcooling, and decreases with the increase of system pressure and valve resistance coefficient. The reason is that an increase in inlet subcooling will result in a decrease in the length of the annular flow, at the same time, the increase of valve resistance will also lead to the decrease of loop flow rate. With the increase of system pressure, the density difference between single-phase and two-phase fluid in the natural circulation loop decreases. Under the same power, the increase of system pressure will lead to the decrease of loop flow rate as well, which will lead to the premature occurrence of boiling criticality.

4.2. The inclination condition

For inclination condition, the channel is assumed to tilt around the x axis, additional force $\boldsymbol{F}$ in Eq. (15) is 0, and the equivalent gravity $\boldsymbol{f}$ is:

$$\boldsymbol{f} = -g_0 \cos\theta \boldsymbol{k} - g_0 \sin\theta \boldsymbol{j} \tag{16}$$

Fig. 10 shows the transient change of mass flux and outlet equilibrium quality of heated channel with the power increasing in a ladder-typed way. In the initial stage, a stationary process is calculated with the power unchanged, and then the inclination condition is introduced and the heating power is gradually increased. The inclination angle is 30°. It can be clearly seen from the figure that once the system inclination occurs, the loop flow rate will be reduced, which can be attributed to the decrease of the loop gravity head.

The trend of CHF in the loop with the inclination angle is demonstrated in Fig. 11, where q_0 is the CHF value under the stationary condition. It can be found that the CHF value decreases with the increase of inclination angle. When the inclination angle is 45°, the CHF of the loop can be reduced to 75% of the original value.

The effect of inclination on CHF of natural circulation loop can be summarized as Fig. 12. The flow characteristic curve of the natural circulation is determined by the loop structure. The inclination of the loop changes the height difference between the heat source and sink, and the flow characteristic curve of the loop changes accordingly. For the natural circulation loop studied in this paper, the inclination of the loop will reduce the position difference of the heat source and sink in the loop, so the system flow rate will also decrease. For the heated section, the liquid film in annular flow region is evenly distributed under stationary state. With the inclination of the loop, the effect of the gravity component in the radial direction causes the non-uniform distribution of the circumferential flow of the liquid film, and the boiling criticality will occur in advance, so the boiling critical approach line will move to the left.

4.3. The rolling condition

For the rolling motion, the loop is assumed to roll around the x axis and the rotation follow the sinusoidal law. The angular velocity is $\boldsymbol{\omega} = -\omega(t)\boldsymbol{i}$, the radius vector is $\boldsymbol{r} = x\boldsymbol{i} + y\boldsymbol{j} + z\boldsymbol{k}$. The Additional force $\boldsymbol{F}$ and the equivalent gravity $\boldsymbol{f}$ are given by:

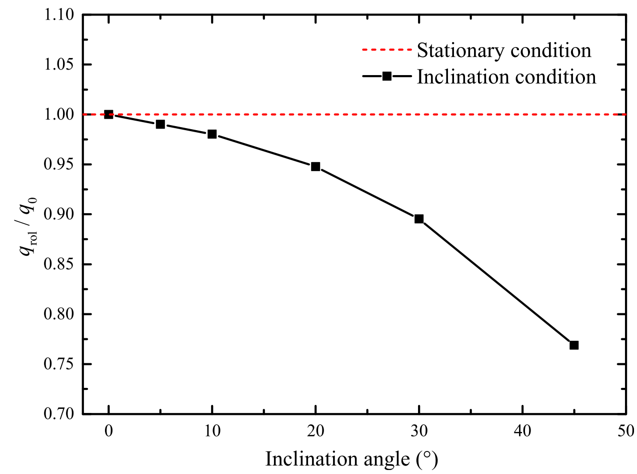


Fig. 11. The trend of CHF in the loop with the inclination angle.

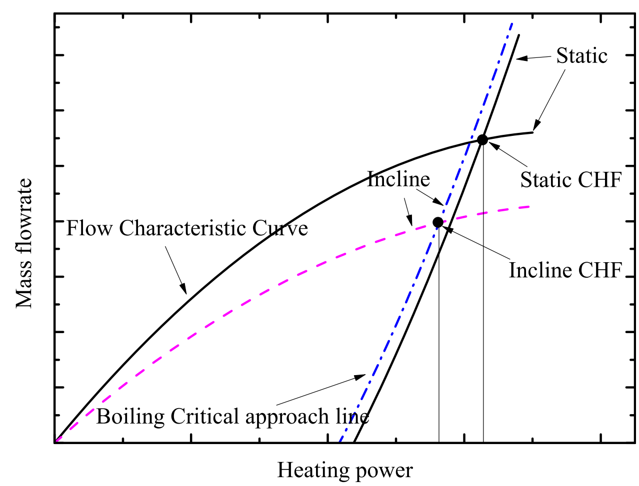


Fig. 12. Schematic of the effect of inclination on CHF in natural circulation.

$$\boldsymbol{F} = -\rho\left[-2\omega(t)u(t)\boldsymbol{j} - \omega^2(t)y\boldsymbol{j} - \omega^2(t)z\boldsymbol{k} + \frac{d\omega(t)}{dt}y\boldsymbol{k} - \frac{d\omega(t)}{dt}z\boldsymbol{j}\right] \tag{17}$$

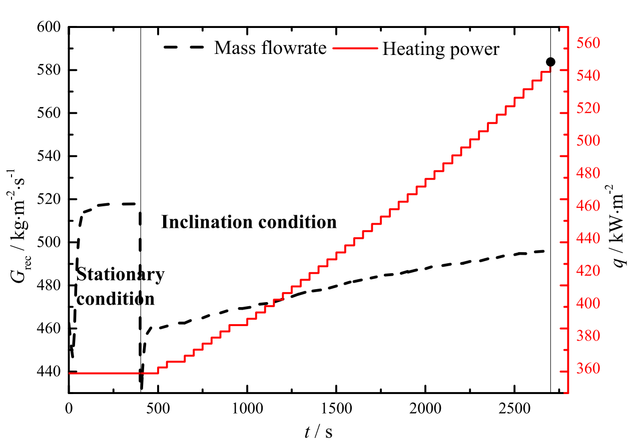


Fig. 10. Transient characteristics of flow under inclination condition.

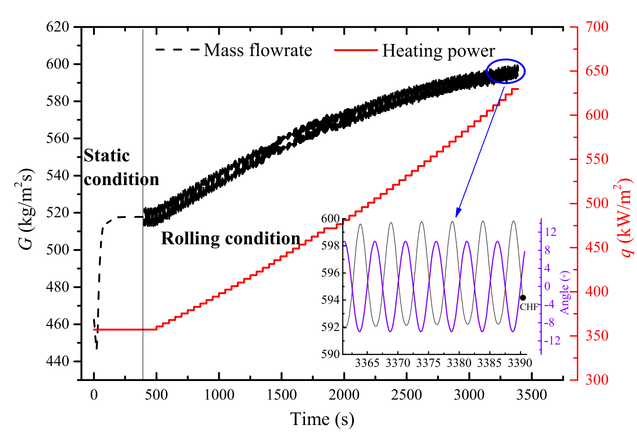


Fig. 13. Transient characteristics of flow under rolling condition.

$$\boldsymbol{f} = -g_0 \cos\theta(t)\boldsymbol{k} - g_0 \sin\theta(t)\boldsymbol{j} \quad (18)$$

Fig. 13 shows the transient change of mass flux with the power increasing in a ladder-typed way. The rolling period is 5s and the rolling amplitude is 10°. Different from the inclination condition, the flow rate in the loop will oscillate periodically with time under the rolling condition, and the oscillation period is consistent with the rolling period. At the same time, boiling criticality does not occur in the trough of oscillating flow, but between the trough value and peak value, which is consistent with the previous research on the CHF of oscillating inlet flow [29].

Figs. 14 and 15 show the trend of CHF in the loop with the rolling amplitude and period. It can be found that the increase of oscillation amplitude and oscillation period will lead to the decrease of CHF, and the value can be reduced by about 15% within the rolling range studied in current paper. In the case of large angular acceleration amplitude, the effect of rolling period on CHF is relatively large. Of course, it should be especially emphasized that the effect of rolling on the CHF in the natural circulation loop is not fixed, which is closely related to the layout of the loop, the position of the rolling fulcrum and the rolling axis.

The effect of rolling motion on CHF of natural circulation loop can be described as Fig. 16. Due to the inclination of the loop caused by the rolling motion and the simultaneous generation of centripetal drive head and tangential drive head, the average system flow rate will decrease, and the system flow rate will fluctuate up and down in the average flow rate. The additional pressure drop caused by the rolling motion will cause the change of the entrainment rate, deposition rate and evaporation rate of the liquid film in annular flow region, and the inclination of the loop will cause the uneven distribution of the liquid film in the circumferential direction of the channel. Under the combined action of the two factors, the boiling critical approach line will move to the left. Moreover, boiling criticality does not occur in the trough of oscillating flow, but between the trough value and peak value, which can be attributed to the stirring effect of the axial flow in the channel [29].

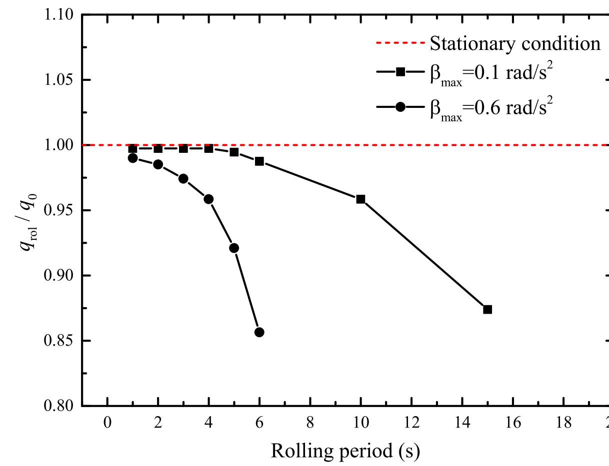


Fig. 15. The trend of CHF in the loop with the rolling period at different angular acceleration amplitudes.

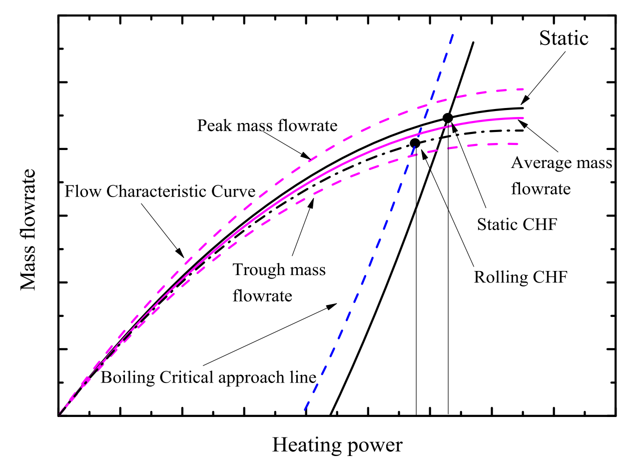


Fig. 16. Schematic of the effect of rolling motion on CHF in natural circulation.

5. Conclusions

Currently, a lot of work has been done on the CHF under normal conditions, but related research under complex motion conditions is limited in publication, which has been reported to have a great influence on CHF characteristics of natural circulation. In this paper, the dryout-type CHF characteristics of natural convection loop under moving condition are studied by a developed CHF analysis program NACOM. Considering that the moving condition would introduce an additional force field and cause flow to oscillate in the loop, an additional force module is coupled to the program. The effects of three operating conditions, namely stationary, inclination and rolling, on the CHF of the loop are preliminary analyzed. Conclusions can be drawn as follows:

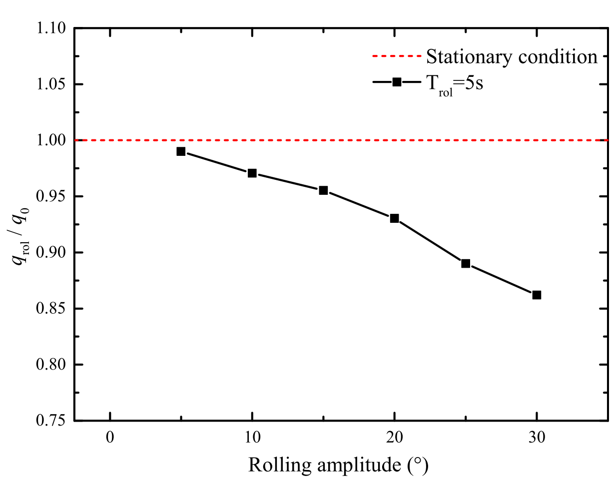


Fig. 14. The trend of CHF in the loop with the rolling amplitude.

(1) Under stationary condition, as expected, the loop CHF increases almost linearly with inlet subcooling of heated channel, and decreases with the increase of system pressure and valve resistance coefficient.
(2) Under inclination condition, the loop CHF decreases with the increase of inclination angle, which is attributed to the decrease of the gravity head of the system and loop flow rate.
(3) Under rolling condition, the flow rate in the loop will oscillate periodically with time and the oscillation period is consistent with the rolling period. The increase of rolling amplitude and rolling period will lead to the decrease of CHF. Especially for the case of large angular acceleration amplitude, the effect of rolling period on CHF is relatively large.
(4) For the moving parameters in this paper, the CHF can be reduced by 25% compared with the static value, which

indicates that it is important to consider the effects of moving condition to retain adequate safety margin in subsequent thermal-hydraulic designs.

It must be made clear that the effect of moving condition on a natural circulation loop is closely related to its own structural arrangement. This work is still proceeding in authors' research, a more detailed discussion about the CHF characteristics of natural circulation under complex moving condition will be in our next research. In addition, due to the scarce data of CHF for motion conditions in publication, the program validation is not enough. More extensive validation and model improvement work needs to be done in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.07.025.

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