

Mechanism of ONB based on nonequilibrium thermodynamics of natural circulation in narrow channels

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Abstract Based on the experiment of onset of nucleate boiling (ONB) in natural circulation and the nonequilibrium thermodynamics dissipative theory, the mechanism of ONB in narrow rectangle channels of natural circulation is proposed. It points out that the onset of nucleate boiling is influenced by the degree of superheat and the special conditions of narrow channels. Under the conditions of both density difference in natural circulation and narrow rectangle channels, the prediction model of ONB in natural circulation of narrow channels based on fluctuating is established. The experimental results show that the present model can be used to predict the heat flux of ONB in narrow rectangle channels. Features of ONB in natural circulation narrow rectangle channels are as follows: heating power is the incentive of the happen of ONB; the higher the heating power is, the higher the degree of superheat is, and the earlier the ONB will appear. With the pressurizing, the appearance of ONB will be delayed. The higher the degree of supercooling is, the later the ONB appears. The ONB will happen easier when there are noncondensable gases and roughness in the channels.

Key words Non-equilibrium thermodynamics, Natural circulation, Onset of nucleate boiling (ONB), Dissipative structure, Degree of superheat

1 Introduction

Natural circulation is an important circulation mode in advanced reactors. It is widely used in the third generation pressurized water reactor AP1000. After the Fukushima accident, scholars around the world pay much attention to the use of natural circulation. ONB influences the safety and the normal operation of the reactors. Natural circulation plays the role of accident mitigation, especially under serious accidents. So the mechanism of ONB is worth to study. A lot of research work on ONB has been reported in recent years^[1-4]. Sudo *et al.*^[5] simulated the subchannel of JRR-3, they had tested and verified the validity of the ONB formula based on superheat. But most of these studies are carried out under the condition of forced

circulation. With the important application of natural circulation in reactor, some scholars began to do experiments under natural circulations^[6]. Siddiqui *et al.*^[7] had pointed out the occurrence conditions of ONB in vertical annular channel under natural circulation and described the relevant influences of heat flux and physical parameters. Majority of these studies are experimental research whereas the ONB formulas are obtained by data fitting. Experimental research on ONB offers the convincing data support, but the data fitting is not enough to describe the occurrence mechanism of ONB properly. In addition, the data processing is relatively complex and various kinds of formulas are proposed. In recent years, advanced mathematical methods were employed for the study of ONB. Zhou *et al.*^[8] studied the computation model of ONB by using unascertained

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mathematics. Wei *et al.*^[9] put forward a new method for ONB, which the artificial neural network was applied to study the ONB in an annular channel. Liu *et al.*^[10] used gray correlation analysis to study ONB under natural circulation. These methods can handle the uncertainty of parameters and the highly nonlinear relationships between the parameters, but could not explore the occurrence reason and mechanism of ONB, especially ONB in narrow rectangle channels under natural circulation. Based on the experimental data and the new perspective of nonequilibrium thermodynamics, the mechanism of ONB in a narrow rectangle channel under natural circulations is studied

in this paper. The ONB superheat formula based on fluctuating is proposed. So the mechanism of ONB under natural circulation in narrow rectangle channels can be analyzed more accurately.

2 Study object

Figure 1 shows the experimental flow chart of natural circulation in the narrow rectangular channels. It consists of preheater, high temperature heater and condenser. The accessory system contains cooling water system, heating system, pressure stable system and medium make-up system.

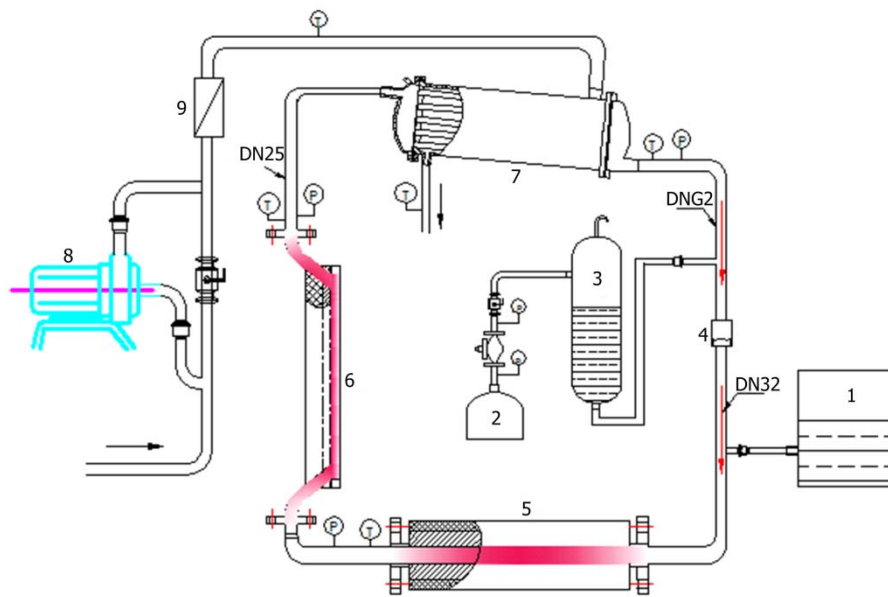


Fig.1 Experimental flow charts of natural circulation in the narrow rectangular channel. 1. Deionized water tank, 2. Nitrogen cylinder, 3. Stabilizer, 4. Turbine flowmeter, 5. Pre-heat section, 6. Visual section, 7. Condenser, 8. Pump, 9. Float flowmeter.

The experimental facility shown in Fig.1 is an evaporation condensation return device using deionized water as its fluid medium. For experiment preparation, the deionized water will fulfill the entire facility by the function of the pump (Fig.1(8)), then the pump will be isolated. The cold water will be heated to a certain degree in the preheating section (Fig.1(5)), and then evaporate in the experimental section. As the density of steam is much less than that of water, the steam will flow up to the condenser (Fig.1(7)) and be cooled. Henceforth the cooled water flows into the downcomer and then flows into the preheater to finish the circulation. In the experiments, the power is laddering up. 15 minutes are needed to

stabilize the experimental condition after each increase in power. The range of the experimental parameters in natural circulation is: heat flux: 0–30 KW, pressure: 0.1–1.5 MPa, inlet temperature: 60–90°C, rate of flow: $0-2.5 \times 10^{-5} \text{ m}^3/\text{s}$.

3 Basic theory

3.1 Nonequilibrium thermodynamics theory

The nonequilibrium thermodynamics is applied to study the thermodynamic variable system and the irreversible open system. In the function of the outside continuous energy flow or materials flow, an open system in non-equilibrium state will go into a new

ordered structure because of the self-organization.

The theory of dissipative structure was first proposed by Prigogine^[11] in 1969. It indicates that the parameters of the nonlinearity open systems which are far away from the equilibrium state will change to a threshold in the progress of energy or materials exchanging with the outside. Due to the fluctuation of the parameters, the system will change and then form and maintain the macro space-time ordered structure.

3.2 Formation mechanism of the dissipative structure

The formation mechanism of the dissipative structure

Table 1 Existed ONB models

Authors	Formulas	Range of parameters
Bergles&Rohsenow ^[12]	$q_{\text{ONB}} = 5.30p^{1.156}[1.8(t_w - t_{\text{sat}})]$ where, $n = 2.41/p^{0.0234}$	(1) Pressure: 0.1–13.6 MPa, ID: 1.6383 mm, OD: 5 mm, forced circulation.
Kandlikar <i>et al.</i> ^[13]	$q_{\text{ONB}} = \frac{\Delta T_{\text{sat}} \cdot \lambda \cdot h_{\text{fg}} \rho_g}{8.8 \cdot \sigma \cdot t_{\text{sat}}}$	(2) Rectangle channel: 3 mm×40 mm, forced circulation.
Hong G, <i>et al.</i> ^[4]	$\Delta T_{\text{sat}} = 0.05 \text{Re}^{0.156} \left(\frac{\rho_g}{\rho_l}\right)^{-0.413} q_{\text{ONB}}^{1.321}$	(3) Rectangle channel: 40 mm×2 mm×1200 mm, mass flow: 298 kg/m ² s–840 kg/m ² s, heat flux: 33–184 kW/m ² , inlet subcooled: 28–55°C, forced circulation.
Zhou tao, <i>et al.</i> ^[14]	$x_{\text{ONB}} = -0.017053 \left(\frac{q_{\text{ONB}}}{Gh_{\text{fg}}}\right)^{0.22045} \text{Pr}_l^{6.18160} \left(\frac{P}{P_j}\right)^{2.06994}$	(4) Pressure: 7.6–13.73MPa, mass flow: 130–340 kg/m ² s, heat flux: 50–440 kW/m ² , natural circulation.

where, q_{ONB} is the heat flux density of ONB, kW/m²; p is the system pressure, MPa; n is an index number; t_w is the wall temperature of ONB, °C; t_{sat} is the saturation temperature, °C; ΔT_{sat} is the degree of superheat, °C; λ is the coefficient of heat conductivity, W/m °C; h_{fg} is the latent heat of vaporization, J/kg; ρ_g is the gas density, kg/m³; σ is the surface tension, N/m; Re is the Reynolds number; ρ_l is the fluid density, kg/m³; Pr_l is the Prandtl number, x_{ONB} is the heat balance dryness of ONB; G is the mass velocity, kg/m²s; P_{li} is the critical pressure, MPa.

4 Occurrence mechanism of natural circulation ONB in narrow rectangular channel

4.1 Generating process of ONB based on the theory of nonequilibrium thermodynamics

The generating process of ONB is that the fluid flowing along the heating surface will change phase when the degree of superheat is high to a certain value.

is the amplification of the system fluctuation. Under a certain threshold, the effect of the fluctuation will weaken and disappear because of the average, so it can not form the new ordered structure. Only when the threshold exceeds a certain value, the fluctuation will be magnified, and then form a new ordered structure.

3.3 Existed ONB models

Most of the existed ONB models are under forced circulation, a few of them are under natural circulation listed in Table 1.

And this is the dynamic evolution process of a bubble from breeding to generate. It is the progress of microscopic fluid phase translating to the macroscopic bubble. The progress includes a series of nonlinear energy release and dissipation such as the internal structure change of the fluid, the breeding and the generation of bubbles. The generated progress of ONB will be divided into three stages based on the theory of nonequilibrium thermodynamics.

(1) Initial stage

In this stage, the fluid temperature rises gradually, the function of heating will change the microstructure of the fluid. At this stage, the fluid is in a nonequilibrium linear area, but the degree of superheat is not high enough to force the fluid produce macro effect.

(2) Disturbance stage

When the superheat degree gradually increases to a certain value, the superheated fluid will be in a nonlinear dynamic area which is away from the equilibrium state. The density fluctuation caused by the degree of superheat will be amplified, and force

the fluid to a stable process through self-organization. The system will go into a new orderly dissipative structure, and produce macroscopic phase transition and bubbles. At this stage, the trigger factor of the phase change is the degree of the superheat.

(3) Breed and generated stage

The bubble has a critical radius of r_c under a certain degree of superheat. The higher the degree of superheat is, the smaller the critical radius of the bubble is. If the bubble size is larger than the critical radius of r_c after the stage of disturbance, the bubble will grow up, otherwise it will annihilate. The generated condition for the bubble in the superheated fluid is that the temperature of the fluid which is r_c away from the heating surface must be higher than the degree of superheat corresponding to the critical radius of r_c . The first bubble generated on the heating surface is ONB.

The occurrence of ONB is a nonlinear progress of saving energy in stable stage and releasing energy in unstable stage. It is a typical progress of nonequilibrium thermodynamics. The occurrence of ONB is a complex process consisting of heat transfer, flow, and phase change. It is a concentrated expression of both dynamic evolutionary process and physical property. The dynamic evolutionary process includes the external heat transfer, flowing condition, inner microcosmic fluid density fluctuation, phase changing, the generation and the growing of a bubble. It is an open progress of irreversible.

4.2 Dissipative structure and feature of ONB generating process

When the superheated degree of the fluid reaches a certain value, the superheated fluid will change phase. The superheated fluid in the heating channel will show up the feature of nonequilibrium dissipative structure. The process from the ONB breeding to its generation is a high irreversible phenomenon of fluid-heating surface system's dissipative structure. The generation of ONB has a closely relationship with the degree of superheat. The fluid temperature grows gradually along the heating narrow channel. The fluid becomes superheated when the temperature exceeds the saturation temperature. Due to energy concentration, the microstructure of the superheated fluid will

dissipate the energy when the superheated degree of the fluid reaches a certain value. The density fluctuation function of the superheated fluid in the nonequilibrium state system will be magnified. Then the superheated fluid will change phase and generate bubbles. In the nonlinear system which is away from the equilibrium state, the density fluctuation plays a role of trigger, tiny fluctuation may lead the system to order dissipative structure, and gets into a new relatively stable stage. The occurrence of ONB shows up the feature of nonlinearity and dissipative structure.

Natural circulation and narrow rectangle channel cause a special feature of flow and heat transfer to the system. By analyzing their influence on the degree of superheat, we can study the occurrence mechanism of ONB in narrow rectangle channel under natural circulation. Natural circulation is the way of energy translation which is driven by the density difference. Compared with forced circulation, natural circulation has the feature of density difference and buoyancy effect. The fluid in natural circulation will enter into nonlinearity stages earlier which are far from the equilibrium state. So, natural circulation will reduce the threshold temperature of the fluid's evaporation. The density fluctuation function will drive the superheated fluid change phase in a lower degree of superheat. Compared with forced circulation, ONB in natural circulation will occur earlier and a lower power is needed. Because of the size effect and space internal circulation together with the non-uniform heating and corner effect, narrow rectangle channel will strengthen the heat transfer. The temperature boundary layer and velocity boundary layer in the narrow rectangle channel are very thin, and the secondary flow will have a strong mixing effect on the boundary layer fluid, so the temperature and velocity in boundary layer will change severely. Compared with the common channel, the narrow rectangle channel system will enter into nonlinearity stages earlier which are far from the equilibrium state. The fluid near the heating wall will achieve superheat state earlier. All these will make the density fluctuation change earlier and then ONB generated.

4.3 Degree of superheat threshold for ONB

As shown in Fig.2, the occurrence of ONB is

restricted by the wall roughness.

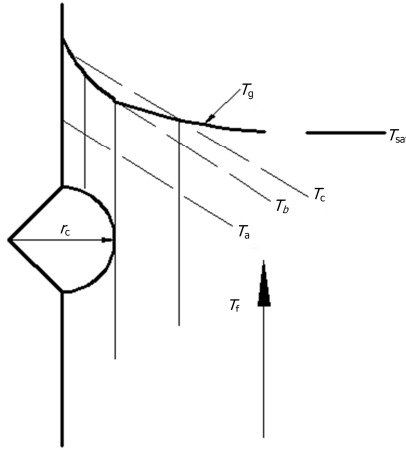


Fig.2 Occurrence of ONB.

In Fig.2, T_g is the bubble growth temperature line. T_a , T_b , T_c are the three bottom laminar flow temperatures. The T_a corresponding degree of superheat is $\Delta T_a = T_a - T_{sat}$. The T_b corresponding degree of superheat is $\Delta T_b = T_b - T_{sat}$. The T_c corresponding degree of superheat is $\Delta T_c = T_c - T_{sat}$. The limit degree of superheat is $\Delta T_g = T_g - T_{sat}$. For $\Delta T_a = \Delta T_g$, so the reentrant cavities will not generate bubbles. For $\Delta T_b = \Delta T_g$, the reentrant cavities may generate bubbles because it is a critical state. For $\Delta T_c = \Delta T_g$, the reentrant cavities will generate bubbles. So under the function of energy dissipation and nonlinear kinetics, the superheated degree of fluid will reach a certain value. And by the fluctuation, the microstructure changes and then the ONB will be generated. When the degree of superheat is under a certain value, the effect of fluctuation will be weakened and disappeared because of average, so the bubble can not be formed. Only when the degree of superheat is over a certain value, the effect of fluctuation will be amplified and produce macro effect, then ONB will be generated.

5 Predictive model of ONB in natural circulation narrow rectangle channel

5.1 ONB degree of superheat formula based on Fluctuation

Most of the existed studies of ONB are based on the macroscopic factor analysis, but the microcosmic evolutionary process of ONB is neglected. From the viewpoint of the microcosmic nonequilibrium thermodynamics, to study the occurrence mechanism

of ONB should confirm that the generating process of ONB has a feature of nonequilibrium thermodynamics. So it is better to study the occurrence mechanism of ONB from the aspect of microstructure.

Zeng *et al.*^[15] studied the limited degree of superheat by fluctuation theory, they put up the ONB degree of superheat presumption based on statistical thermodynamics and fluctuation theory. They had got the limit of homogeneity boiling in Gibbs canonical ensemble. And based on the Gibbs canonical ensemble, it shows as follows.

$$2\sigma\{p_s \exp[v_1(p_1 - p_s)/RT - p_1]\}^{-1} = kT^2 C'_v / 12\pi\sigma^2 \quad (5)$$

$$\Delta T_s = T - T_s \quad (6)$$

where, σ is the surface tension, N/m. p_s is the saturation pressure, Pa. v_1 is the fluid specific volume, m^3/s , p_1 is the pressure, Pa. R is the scale factor, about 8.314 J/(mol·K). T is the wall temperature, K. k is the boltzmann's constant. C'_v is the system's constant volume, kJ/(kg·°C). ΔT_s is the limit degree of superheat, K. T_s is the saturation temperature, K.

The limit degree of superheat under heterogeneous boiling was put forward by Liu *et al.*^[16] in 1997, combined with the above Gibbs canonical ensemble, it shows as follow:

$$(4\rho_1 c_v kT^2 / 3)^{1/2} (\pi r_c F)^{-1/2} = a (\sigma + br_c p_1 \varepsilon) \quad (7)$$

where, ρ_1 is the fluid density, kg/m³. c_v is the specific heat. r_c is the critical radius, m. F is the free energy reduced factor. a and b stand for the different work model. ε is the molecular average energy, J. The other parameters are the same above.

In Zeng and Liu's studies, they did not take account of flow boiling, they thought the wall was absolutely smooth and the fluid was absolutely pure. In the flow boiling, the wall is inevitable exist of a certain roughness, and there is noncondensable gas in the gasification core. So the degree of superheat in boiling flow is much lower than the degree of superheat in homogeneous boiling.

In order to study the bubble behavior in forced circulation, Pan *et al.*^[17] did experiments in a 2 mm wide narrow rectangular channel. He found that at the initial growing stage, the bubble size is about 10^{-2} mm, and the bubble's static growing time on the wall is less than 0.5 ms. In the study of this issue^[18], it

finds that, in a 2 mm wide narrow rectangular channel, the bubble diameter under natural circulation is 10^{-2} – 10^{-1} mm, and the bubble's static growing time on the wall is 1–2 s. Compared with the forced circulation, the bubble growth cycle under natural circulation is longer. In the computation, flow velocity in the near wall place is small enough under natural circulation, the bubble's grow process is kin to static process. Guo *et al.*^[19] studied the natural circulation flow boiling, and he put forward the bubble formula in natural circulation as below:

$$r_c = \left[\frac{3\sigma f(\theta)}{2(\rho_l - \rho_g)g} \right]^{0.5} \quad (8)$$

Based on the energy conservation, to form a bubble with the critical radius of r_c , the needed work is the plus work of surface tension and volume expansion, that is

$$\begin{aligned} W_{cr} &= \sigma A + p_l \Delta V \\ &= 4\pi r_c^2 \sigma + \frac{4}{3} \pi r_c^3 (1 - \rho_v / \rho_l) p_l \end{aligned} \quad (9)$$

Based on Eq.(9), considering the wall surface contact angle and free energy reduction factor, to form a spherical crown, the minimum work is

$$\begin{aligned} W_{cr} &= f \cdot [\xi_1 (\sigma A) + \xi_2 (p_l \Delta V)] \\ &= a \pi r_c^2 f [\sigma + b r_c p_l \beta] \end{aligned} \quad (10)$$

Where, ξ_1 and ξ_2 are the proportion spherical crown take a spherical. h_{fg} is the latent heat of vaporization, kJ/kg. $\beta = 1 - \rho_v / \rho_l$, $f = (2 + 3\cos\theta - \cos^3\theta)/4$, θ is the contact angle. T_{sat} is the saturation temperature, °C. k_l is the thermal diffusivity. P_f is the liquid pressure, MPa. P_t is the total pressure, MPa. q is the heat flux, kW/m². A is the spherical superficial area, m². ΔV is the spherical volume, m³. The other parameters are the same above.

Liu *et al.*^[16] pointed out that, in the Gibbs canonical ensemble the energy fluctuation is:

$$\Delta E = (kT^2 C_v)^{1/2} = \sqrt{4kT^2 \pi r_c^3 \rho_l c_v / 3} \quad (11)$$

where, ΔE is the energy fluctuation in Gibbs canonical ensemble. The other parameters are the same above.

Supposed that the energy fluctuation in canonical ensemble is equal to the work needed to form a bubble, that is

$$\Delta E = W_{cr} \quad (12)$$

where, W_{cr} is the work needed to form a bubble.

If we put Eqs.(10) and (11) into Eq.(12), then it can be got that:

$$(4kT^2 \pi r_c^3 \rho_l c_v / 3)^{1/2} (a \pi r_c^2 f)^{-1} = \sigma + b r_c p_l \beta \quad (13)$$

To get the relationship between the critical radius and the degree of superheat in natural circulation, we can put Eq.(8) into Eq.(13).

5.2 ONB modeling in natural circulation narrow rectangle channel

Based on the ONB nonequilibrium thermodynamics mechanism put forward by this study, the fluid degree ($t_f - t_{sat}$) of superheat near the wall is the key factor which triggers the occurrence of ONB. At the same time, use $Pr \cdot Gr$ to reflect the motion characteristic which is caused by the density difference in natural circulation, and introduce the dimensionless factor a as the strengthen heat transfer factor in narrow rectangular channels. The ONB heat flux q_{ONB} needed in natural circulation narrow rectangle channel can be expressed as the function of ($t_f - t_{sat}$), $Pr \cdot Gr$ and a , that is:

$$\begin{aligned} q_{ONB} &= f((t_f - t_{sat}), Pr \cdot Gr, a) \\ &= f(b(t_w - t_{sat}), Pr \cdot Gr, a) \end{aligned} \quad (14)$$

where, $b = (t_f - t_{sat}) / (t_w - t_{sat})$; t_f is the fluid temperature, °C. t_{sat} is the saturation temperature, °C. Pr is the Prandtl number. Gr is the Grashof number. t_w is the wall temperature, °C. a is the strengthen heat transfer factor in the narrow rectangle channel.

5.3 ONB model analysis and test in natural circulation narrow rectangle channel

Supposed $q_{ONB} = a(Pr \cdot Gr)^m [b(\Delta t_{sat})]^n$, based on the experimental data of this study^[18], the undetermined constant m , n could be solved. And the semiempirical relation of ONB in narrow rectangle channel under natural circulation is:

$$\begin{aligned} q_{ONB} &= 2.7858 (Gr \cdot Pr)^{0.5961} [0.72 (\Delta t_{sat})]^{0.115} \\ &= 2.6825 (Gr \cdot Pr)^{0.5961} (\Delta T_{sat})^{0.115} \end{aligned} \quad (15)$$

The application conditions of Eq.(15) are given as follows: the working medium is water, the pressure is between 0.1–1.5 Mpa, the mass flow rate is between 0–0.025 kg/s, the inlet temperature is between 10–90°C, the channel is narrow rectangle.

Figure 3 shows the data comparison between

the calculated value (y-axis) and the experimental value (x-axis). Compared with the experimental value, the error of the ONB calculated value is located in the margin of $\pm 30\%$. This formula could be used to forecast the needed ONB heat flux under experimental conditions. For the occurrence of ONB, the data have a high dispersion degree due to the complexity.

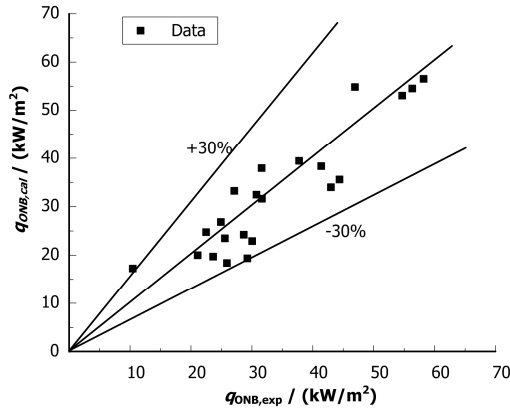


Fig.3 Comparison of the calculated value with the experimental value.

6 Influence of different factors on ONB in natural circulation narrow rectangle channel

6.1 Influence of wall degree of superheat on ONB

From the heat flux formulas of ONB in Table 1 and Eq.(15), it can be seen that the variation trend of the ONB heat flux with the wall degree of superheat is shown in Fig.4.

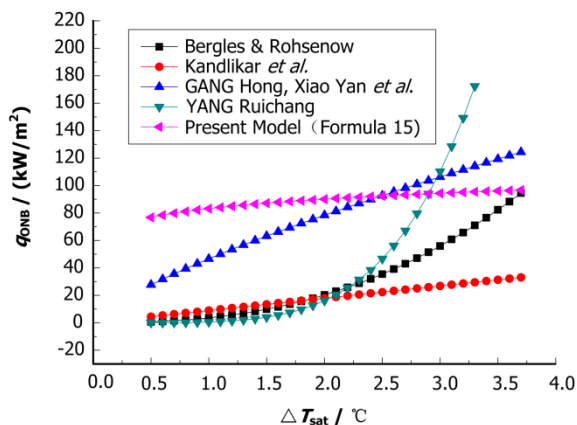


Fig.4 ONB heat flux changes with wall degree of superheat.

As shown in Fig.4, with the growing of wall heat flux, the ONB heat fluxes which are computed by the formulas in Table 1 and the present model are

growing. YANG's model changes slowly at the beginning, but because the pressure in Fig.4 is smaller than the experimental pressure of YANG's, so it changes dramatically with the growing of the superheated degree. At a lower degree of superheat, the heat flux of YANG Ruichang's model is the smallest, but increases with the growing of superheated degree its heat flux gradually, and exceed the other models at last. The present model has a higher ONB heat flux than both Bergles&Rohsenow and Kandlikar's models at the same condition. At a lower degree of superheat, the heat flux of the present model is higher than GANG's, but with the growing of wall's superheated degree the heat flux of the present model begins to lower than GANG's, the change of the present model is slow.

The reason why the lines change as figure 4 shows is that they had different types of channels.

Comparing the models of Gang Hong's with the present model, it can be seen that the present model has a lower ONB heat flux at the initial stage, which means the ONB in natural circulation will appear easier. Based on the ONB non-equilibrium thermodynamics and superheated degree leading mechanism put forward by part 3, fluid degree of superheat is the trigger factor for ONB. But heat power is not the only factor that influences superheated degree, it is a combined action. Heating power is the original cause of natural circulation, it is the source of fluid saving energy and the incentive of superheat fluid. The higher the heating power is, the higher the degree of superheat is, and the ONB will appear earlier. It is obvious that the ONB in natural circulation will appear earlier than it is in forced circulation with the same condition.

Heating power is the leading control factor in natural circulation, it has a bigger density difference than in forced circulation, so the heat transfer ability in natural circulation will be weakened. With a slight increase in heat flux, the wall temperature may grow rapidly, and the wall temperature will be higher than that in forced circulation, and this will lead to a higher degree of superheat. So in the later stage, the heat flux calculated by Gang's model is higher than that calculated by the present model.

6.2 Influence of system pressure on ONB

When the internal bubble pressure is larger than the fluid pressure, the bubble will grow. Only under this condition, the internal bubble pressure will work and the mechanical energy will transfer into the fluid's kinetic energy, and the bubble will grow up. Fig.5 shows the influence of system pressure on the ONB heat flux.

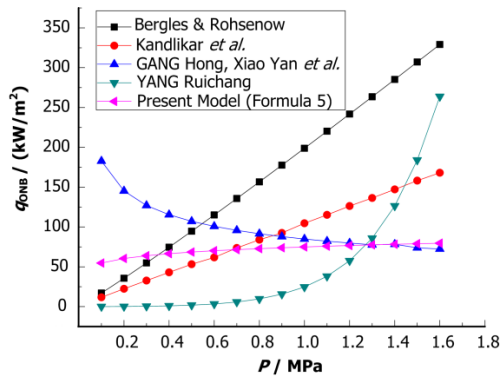


Fig.5 Influence of system pressure on ONB heat flux.

As shown in Fig.5, with the growing of system pressure, the ONB heat fluxes computed by Bergles&Rohsenow and Kandlikar's model are increased, but decreased in Gang's model. The ONB heat flux changes slowly in the present model, and in Yang's model it changes gently and with a lower heat flux at first, but with the pressure growing, the heat flux increases rapidly.

The system pressure has a dual function on the ONB, on the one hand the pressure increases, the thermal resistance will increase, then the gathered local heat will make the nucleus of boiling increase. All these will make the bubble occur earlier, which means the appearance of ONB at a lower heat flux. On the other hand, the increase of pressure will lead to the decrease of the density difference, so the bubble is hard to grow up and hard to break away from the heating wall. It will lengthen the heating process. All these will make the bubble occur later, which means the appearance of ONB at a higher heat flux. In Bergles & Rohsenow and Kandlikar's models the increase of system pressure will restrain the bubble grown, and with the rise of system pressure the fluid saturation temperature will grow, these will lead to the drop of fluid degree of superheat, so pressure increase will make the ONB occur later. In the models of Gang

and the present, there isn't the direct influence of pressure and the both experiments are taken in normal pressure. The pressure does not have a significant influence on the parameter of density. So in Gang's model the heat flux decreases with the pressure. The present model changes gently. YANG's experiment was taken under the pressure of 7–22.1 MPa, the pressure has a direct influence on the latent heat of vaporization, it will greatly influence the dryness. All of these will lead to a fairly large change of the ONB heat flux.

6.3 Influence of inlet degree of subcooling on ONB

The influence of the inlet degree of subcooling on ONB heat flux is shown in Fig.6. With the growing of the inlet degree of subcooling, the ONB heat flux computed by the models in Table 1 is increased. But the increase of amplitude in Yang's is large, and it has a different magnitudes order with others.

The reason is that only when the bubble interface temperature is lower than the surrounding fluid temperature, the fluid will transfer heat to the bubble, and gasify on the interface. So the lower the inlet degree of subcooling is, the easier the ONB appears. When the other conditions are the same, the rise of the degree of subcooling will make the fluid temperature relatively low at the same position. It goes against the bubble gasify, and thus restrains the occurrence of ONB. In the flow structure of natural circulation, speed couples with the heating. And with the quantity of heat increasing, the total flow will increase. Heating will make the mass velocity in the boundary layer significantly be reduced. The higher the temperature is in the boundary layer, the more significant reducing of the mass velocity is. Because of the boundary layer effect, the flow velocity in the middle of the channel will increase obviously. So compared with forced circulation, the velocity of bullet-like parabolic distribution is more gentle. Thus, the speed difference in the fluid velocity boundary layer will increase. So the calculated value in Bergles&Rohsenow and Kandlikar *et al.*'s models is larger than the present model. Which means that under the same conditions, ONB in natural circulation will appear earlier than in forced circulation. In addition,

though Yang's model is under natural circulation as the present model, its object of study is annular channel, the features of narrow rectangle and secondary flow in this study will make it earlier to occur ONB than in annular channel. Yang's experiment was taken under the pressure of 7–22.1 MPa, the pressure has a direct influence on the latent heat of vaporization, it will greatly influence the dryness. In this study the pressure is located in 0.1–3.4 MPa. So Yang's model has a great difference with the other models.

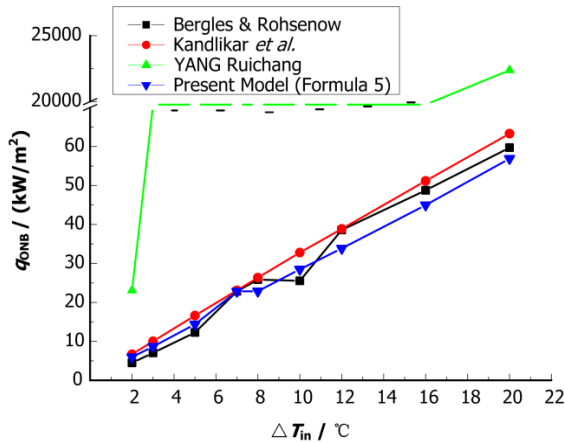


Fig.6 Influence of the inlet degree of subcooling on ONB.

6.4 Influence of non-condensable gas and wall roughness on ONB

On the wall surface, there are certain size nicks and reentrant cavities, these tiny reentrant cavities will capture the non-condensable gas, steam or other impurities. The fluid in the channel could not be absolutely pure, it will include some non-condensable gas or impurities. These reentrant cavities on the wall surface or impurities may be the nucleation center of bubbles^[20], as shown in Fig.7.

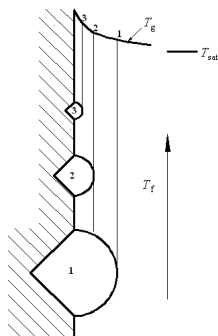


Fig.7 Influence of Wall Roughness on ONB

Figure 7 tells that, 1, 2, 3 represent the different size gasification cores. As Fig.2 tells, with the bubble grows its temperature needs to get the growth curve ΔT_g . In Fig.7, the wall roughness $1 > 2 > 3$, for the 1, 2, 3, corresponding wall degree of superheat $\Delta T_1 = T_{g1} - T_{sat}$, $\Delta T_2 = T_{g2} - T_{sat}$, $\Delta T_3 = T_{g3} - T_{sat}$. It can be seen from Fig.7, $T_{g1} < T_{g2} < T_{g3}$, so $\Delta T_1 < \Delta T_2 < \Delta T_3$, that means the rougher the wall is, the easier the ONB appeared. If there is non-condensable gas in bubbles, the steam partial pressure will decay. So the bubble can get critical state in a lower absorbed heat. Noncondensable gas and wall roughness can reduce the needed degree of superheat that leads fluid to phase change, and also will make the fluid easier to get non-equilibrium state. So if there are non-condensable gas and wall roughness in the system, it is easier for the occurrence of ONB.

7 Conclusion

The formula of ONB limit superheated degree based on the energy fluctuation theory is proposed. According to the nonequilibrium thermodynamics and dissipation theory, the occurrence mechanism and the computation model of the ONB in narrow rectangle channel under natural circulation are put forward, and the computed result is verified by experiment. And finally the ONB features in narrow rectangle channel under natural circulation are analyzed. The summary of our work is listed as below:

(1) The occurrence of ONB is induced by the degree of superheat. The bigger the heating power is, the bigger the degree of superheat is, and the ONB will occur earlier. But it still will be influenced by the external environment.

(2) Compared with forced circulation, the fluid in natural circulation will enter into nonlinearity stages which are far from the equilibrium state earlier. So, natural circulation will reduce the fluid's threshold temperature of evaporation. Which will lead to an earlier density fluctuation and the occurrence of ONB.

(3) Narrow rectangle channel has the effect of secondary flow. Compared with the normal channel, the system will enter into nonlinearity stages. The fluid near the wall will also enter into the superheat state earlier, and the narrow rectangle channel will lead to an earlier density fluctuation.

(4) With the increase of pressure, the ONB will occur later. The bigger the inlet degree of subcooling is, the later the ONB occurs. If there is non-condensable gas in the system and the wall is rough, the ONB will occur easily.

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