Mechanism of ONB Based on Nonequilibrium Thermodynamics of Natural Circulation in Narrow Channels (Postprint)

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Abstract

Based on experiments on the onset of nucleate boiling (ONB) in natural circulation and the dissipative theory of nonequilibrium thermodynamics, a mechanism for ONB in narrow rectangular channels under natural circulation conditions is proposed. It indicates that the onset of nucleate boiling is influenced by the degree of superheat and the special conditions characteristic of narrow channels. Under conditions involving both the density difference that drives natural circulation and the narrow rectangular channel geometry, a predictive model for ONB in narrow-channel natural circulation based on fluctuation theory is established. Experimental results demonstrate that the proposed model can predict the heat flux at ONB in narrow rectangular channels. The characteristics of ONB in natural circulation narrow rectangular channels are as follows: heating power serves as the trigger for ONB; as heating power increases, the degree of superheat increases, and ONB occurs earlier. Increasing pressure delays the onset of ONB. Greater subcooling leads to delayed ONB occurrence. ONB occurs more readily in the presence of noncondensable gases and surface roughness within the channels.

Full Text

Preamble

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Mechanism of ONB Based on Nonequilibrium Thermodynamics of Natural Circulation in Narrow Channels

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Abstract

Based on experiments of onset of nucleate boiling (ONB) in natural circulation and nonequilibrium thermodynamics dissipative theory, this paper proposes a mechanism for ONB in narrow rectangular channels under natural circulation. It identifies that ONB is influenced by the degree of superheat and the special conditions of narrow channels. Under the combined conditions of density difference in natural circulation and narrow rectangular channels, a prediction model for ONB in natural circulation of narrow channels is established based on fluctuation theory. Experimental results demonstrate that the present model can predict the heat flux of ONB in narrow rectangular channels. Key features of ONB in natural circulation narrow rectangular channels are: heating power provides the incentive for ONB occurrence; higher heating power leads to higher superheat degree and earlier ONB appearance. With increasing pressure, ONB appearance is delayed. Higher subcooling degree causes later ONB appearance. ONB occurs more readily when noncondensable gases and surface roughness are present in the channels.

Keywords

Nonequilibrium thermodynamics, Natural circulation, Onset of nucleate boiling (ONB), Dissipative structure, Degree of superheat

Introduction

Natural circulation represents an important circulation mode in advanced reactors and is widely employed in the third-generation pressurized water reactor AP1000. Following the Fukushima accident, scholars worldwide have devoted considerable attention to natural circulation applications. ONB significantly influences reactor safety and normal operation, with natural circulation playing a crucial role in accident mitigation, particularly under severe accident conditions. Consequently, investigating the ONB mechanism is of substantial importance.

Numerous studies on ONB have been reported in recent years [1 4]. Sudo et al. [5] simulated the subchannel of JRR-3 and verified the validity of ONB correlations based on superheat. However, most existing research has been conducted under forced circulation conditions. Given the important application of natural circulation in reactors, some scholars have begun experimental investigations under natural circulation conditions [6]. Siddiqui et al. [7] identified occurrence conditions for ONB in vertical annular channels under natural circulation and described the relevant influences of heat flux and physical parameters. The majority of these studies remain experimental, with ONB correlations obtained through data fitting. While experimental research provides convincing data support, data fitting alone is insufficient to properly describe the underlying occurrence mechanism of ONB. Additionally, data processing is relatively complex, yielding various proposed correlations.

In recent years, advanced mathematical methods have been applied to ONB studies. Zhou et al. [8] investigated computational models of ONB using unascertained mathematics. Wei et al. [9] proposed a new method for ONB analysis, applying artificial neural networks to study ONB in annular channels. Liu et al. [10] employed gray correlation analysis to investigate ONB under natural circulation. These methods can handle parameter uncertainty and highly nonlinear relationships but cannot explore the fundamental reasons and mechanisms of ONB, particularly in narrow rectangular channels under natural circulation. Based on experimental data and a new perspective of nonequilibrium thermodynamics, this paper investigates the mechanism of ONB in narrow rectangular channels under natural circulation. An ONB superheat formula based on fluctuation theory is proposed, enabling more accurate analysis of the ONB mechanism in narrow rectangular channels under natural circulation.

2 Study Object

The experimental flow diagram for natural circulation in narrow rectangular channels is shown in Figure 1 [Figure 1: see original paper]. The system consists of a preheater, high-temperature heater, and condenser, with auxiliary systems including cooling water, heating, pressure stabilization, and medium makeup subsystems.

The experimental facility shown in Fig. 1 is an evaporation-return device using deionized water as the working fluid. During experimental preparation, deionized water fills the entire facility via the pump (Fig. 1(8)), after which the pump is isolated. Cold water is heated to a specified temperature in the preheating section (Fig. 1(5)) and then evaporates in the experimental section. Since steam density is much lower than water density, steam flows upward to the condenser (Fig. 1(7)) for cooling. The cooled water then flows into the downcomer and returns to the preheater, completing the circulation. During experiments, power is increased in steps, with 15 minutes required to stabilize conditions after each power increment. The experimental parameter ranges for natural circulation are: heat flux: 0 30 kW, pressure: 0.1 1.5 MPa, inlet temperature: 60 90ºC, flow rate: 0 2.5\$×10^{-5}\$ m^3/s.

3.1 Nonequilibrium Thermodynamics Theory

Nonequilibrium thermodynamics is applied to study thermodynamic variable systems and irreversible open systems. Under the influence of continuous external energy or material flow, an open system in a nonequilibrium state can evolve into a new ordered structure through self-organization.

The theory of dissipative structures was first proposed by Prigogine [11] in 1969. It indicates that for nonlinear open systems far from equilibrium, parameters will change to a threshold during energy or material exchange with the external environment. Due to parameter fluctuations, the system will transform and subsequently form and maintain a macroscopic spatiotemporal ordered structure.

3.2 Formation Mechanism of the Dissipative Structure

The formation mechanism of dissipative structures involves the amplification of system fluctuations. Below a certain threshold, fluctuation effects weaken and disappear due to averaging, preventing the formation of new ordered structures. Only when the threshold exceeds a specific value will fluctuations be amplified, leading to the formation of a new ordered structure.

3.3 Existing ONB Models

Most existing ONB models were developed for forced circulation, with only a few applicable to natural circulation, as listed in Table 1 .

Table 1. Existing ONB Models

Authors	Formulas	Range of Parameters
Bergles & Rohsenow [12]	q_{ONB} = $5.30p^{1.156[1.8(t\_w - t\_{sat})]}$	Pressure: 0.1 13.6 MPa, ID: 1.6383 mm, OD: 5 mm, forced circulation
Kandlikar et al. [13]	Rectangle channel: 3 mm × 40 mm, forced circulation	
Hong G, et al. [4]	Rectangle channel: 40 mm × 2 mm × 1200 mm, mass flow: 298 kg/m^2s 840 kg/m^2s, heat flux: 33 184 kW/m^2, inlet subcooling: 28 55ºC, forced circulation	
Zhou tao, et al. [14]	(4)	Pressure: 7.6 13.73 MPa, mass flow: 130 340 kg/m^2s, heat flux: 50 440 kW/m^2, natural circulation

where q_{ONB} is the heat flux density of ONB (kW/m^2); p is system pressure (MPa); n is an index number; t_w is the wall temperature at ONB (ºC); t_{sat} is the saturation temperature (ºC); ΔT_{sat} is the degree of superheat (ºC); λ is the thermal conductivity (W/m·ºC); h_{fg} is the latent heat of vaporization (J/kg); _g is the gas density (kg/m^3); σ is the surface tension (N/m); Re is the

Reynolds number; _l is the fluid density (kg/m^3); Pr_l is the Prandtl number; x_{ONB} is the heat balance dryness at ONB; G is the mass velocity (kg/m^{2}s); P_{li} is the critical pressure (MPa).

4 Occurrence Mechanism of ONB in Natural Circulation Narrow Rectangular Channels

4.1 Generating Process of ONB Based on Nonequilibrium Thermodynamics Theory

The generating process of ONB involves fluid flowing along the heating surface changing phase when the superheat degree reaches a certain value. This represents the dynamic evolution of a bubble from nucleation to generation—the transition from microscopic fluid phase to macroscopic bubble. This process includes a series of nonlinear energy release and dissipation events, such as internal fluid structural changes, bubble nucleation, and bubble generation. Based on nonequilibrium thermodynamics theory, the ONB generation process can be divided into three stages:

(1) Initial Stage
In this stage, fluid temperature rises gradually, and heating alters the fluid's microstructure. The fluid exists in a nonequilibrium linear region, but the superheat degree is insufficient to produce macroscopic effects.

(2) Disturbance Stage
When the superheat degree gradually increases to a certain value, the superheated fluid enters a nonlinear dynamic region far from equilibrium. Density fluctuations caused by superheat are amplified, forcing the fluid toward a stable process through self-organization. The system evolves into a new ordered dissipative structure, producing macroscopic phase transition and bubbles. At this stage, the trigger factor for phase change is the degree of superheat.

(3) Nucleation and Generation Stage
A bubble has a critical radius r_c under a certain superheat degree. The higher the superheat degree, the smaller the bubble's critical radius. If bubble size exceeds the critical radius r_c after the disturbance stage, the bubble will grow; otherwise, it will collapse. The generation condition for a bubble in superheated fluid requires that the fluid temperature at a distance r_c from the heating surface must be higher than the superheat degree corresponding to the critical radius r_c. The first bubble generated on the heating surface marks ONB.

ONB occurrence represents a nonlinear process of energy storage during stable stages and energy release during unstable stages—a typical nonequilibrium thermodynamic process. ONB is a complex process involving heat transfer, flow, and phase change, representing a concentrated expression of both dynamic evolutionary processes and physical properties. The dynamic evolutionary process includes external heat transfer, flow conditions, internal microscopic fluid density fluctuations, phase change, and bubble generation and growth. It is an open, irreversible process.

4.2 Dissipative Structure and Features of ONB Generating Process

When the superheat degree of fluid reaches a certain value, the superheated fluid changes phase. The superheated fluid in the heating channel exhibits characteristics of a nonequilibrium dissipative structure. The process from ONB nucleation to generation is a highly irreversible dissipative structure phenomenon of the fluid-heating surface system. ONB generation has a close relationship with the degree of superheat. Fluid temperature increases gradually along the heating narrow channel, becoming superheated when exceeding the saturation temperature. Due to energy concentration, the microstructure of superheated fluid will dissipate energy when the superheat degree reaches a certain value. The density fluctuation function of superheated fluid in the nonequilibrium state system will be magnified, causing the superheated fluid to change phase and generate bubbles. In the nonlinear system far from equilibrium, density fluctuations act as a trigger, where tiny fluctuations may lead the system to an ordered dissipative structure, entering a new relatively stable stage. ONB occurrence demonstrates features of nonlinearity and dissipative structure.

Natural circulation and narrow rectangular channels cause special flow and heat transfer characteristics in the system. By analyzing their influence on the superheat degree, we can study the ONB occurrence mechanism in narrow rectangular channels under natural circulation. Natural circulation is an energy translation method driven by density difference. Compared with forced circulation, natural circulation features density difference and buoyancy effects. Fluid in natural circulation enters nonlinear stages far from equilibrium earlier, reducing the fluid's evaporation threshold temperature. The density fluctuation function will drive superheated fluid to change phase at a lower superheat degree. Consequently, ONB in natural circulation occurs earlier and requires lower power than in forced circulation.

Due to size effects, non-uniform heating, and corner effects, narrow rectangular channels enhance heat transfer. The temperature boundary layer and velocity boundary layer in narrow rectangular channels are very thin, and secondary flow produces strong mixing effects on boundary layer fluid, causing severe temperature and velocity changes in the boundary layer. Compared with conventional channels, narrow rectangular channel systems enter nonlinear stages far from equilibrium earlier. Fluid near the heating wall achieves superheat state earlier, and density fluctuations change earlier, leading to earlier ONB generation.

4.3 Degree of Superheat Threshold for ONB

As shown in Fig. 2 [Figure 2: see original paper], ONB occurrence is restricted by wall roughness. The generating process of ONB should confirm that ONB has features of nonequilibrium thermodynamics, making it preferable to study the occurrence mechanism from the microstructure perspective.

Zeng et al. [15] studied the limiting superheat degree using fluctuation theory, proposing an ONB superheat degree presumption based on statistical thermodynamics and fluctuation theory. They obtained the limit of homogeneous boiling in the Gibbs canonical ensemble, expressed as follows:

[The equation would appear here]

In Fig. 2, T_g is the bubble growth temperature line. T_a, T_b, T_c are three bottom laminar flow temperatures. The superheat degree corresponding to T_a is ΔT_a = T_a - T_{sat}. The superheat degree corresponding to T_b is ΔT_b = T_b - T_{sat}. The superheat degree corresponding to T_c is ΔT_c = T_c - T_{sat}. The limit superheat degree is ΔT_g = T_g - T_{sat}. For ΔT_a = ΔT_g, reentrant cavities will not generate bubbles. For ΔT_b = ΔT_g, reentrant cavities may generate bubbles because it is a critical state. For ΔT_c = ΔT_g, reentrant cavities will generate bubbles. Therefore, under the influence of energy dissipation and nonlinear kinetics, the superheated fluid reaches a certain value. Through fluctuation, microstructure changes occur and ONB is generated. When the superheat degree is below a certain value, fluctuation effects weaken and disappear due to averaging, preventing bubble formation. Only when the superheat degree exceeds a certain value will fluctuation effects be amplified to produce macroscopic effects, leading to ONB generation.

5 Predictive Model of ONB in Natural Circulation Narrow Rectangular Channels

5.1 ONB Superheat Degree Formula Based on Fluctuation

Most existing ONB studies are based on macroscopic factor analysis, neglecting the microscopic evolutionary process of ONB. From the perspective of microscopic nonequilibrium thermodynamics, studying the occurrence mechanism requires consideration of fluctuation effects. The limit superheat degree under heterogeneous boiling was proposed by Liu et al. [16] in 1997. Combined with the Gibbs canonical ensemble, it is expressed as follows:

[The equation would appear here]

where _l is the fluid density (kg/m^3), c_v is the specific heat, r_c is the critical radius (m), F is the free energy reduction factor, a and b represent different work models, and is the molecular average energy (J). Other parameters are as defined above.

In Zeng and Liu's studies, they did not consider flow boiling, assuming the wall was absolutely smooth and the fluid was absolutely pure. In flow boiling, the wall inevitably has certain roughness, and noncondensable gas exists in nucleation sites. Therefore, the superheat degree in flow boiling is much lower than in homogeneous boiling.

To study bubble behavior in forced circulation, Pan et al. [17] conducted experiments in a 2 mm wide narrow rectangular channel. They found that at the initial growth stage, bubble size was about 10^{-2} mm, and the bubble's static growth time on the wall was less than 0.5 ms. In related studies [18], it was found that in a 2 mm wide narrow rectangular channel under natural circulation, bubble diameter ranged from 10^{-2} to 10^{-1} mm, and the bubble's static growth time on the wall was 1 2 s. Compared with forced circulation, the bubble growth cycle under natural circulation is longer. In calculations, flow velocity near the wall under natural circulation is small enough that the bubble growth process can be approximated as static.

Guo et al. [19] studied natural circulation flow boiling and proposed the following bubble formula for natural circulation:

[The equation would appear here]

Based on energy conservation, to form a bubble with critical radius r_c, the required work equals the sum of surface tension work and volume expansion work. Based on this principle and considering wall surface contact angle and free energy reduction factor, the minimum work to form a spherical cap is:

[The equation would appear here]

where $_1$ and $_2$ are proportionality factors, h_{fg} is the latent heat of vaporization, f = (2 + 3cos - cos^3)/4, is the contact angle, β = 1 - _v/ _l, T_{sat} is the saturation temperature (ºC), k$_1$ is thermal diffusivity, P_f is liquid pressure (MPa), P_t is total pressure (MPa), q is heat flux (kW/m^2), A is spherical surface area (m^2), and ΔV is spherical volume (m^3). Other parameters are as defined above.

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

[The equation would appear here]

where ΔE is energy fluctuation in the Gibbs canonical ensemble. Other parameters are as defined above.

Assuming the energy fluctuation in the canonical ensemble equals the work needed to form a bubble:

[The equation would appear here]

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

Substituting the relevant equations yields:

[The equation would appear here]

To obtain the relationship between critical radius and superheat degree in natural circulation, the appropriate equation can be substituted into this expression.

5.2 ONB Modeling in Natural Circulation Narrow Rectangular Channels

Based on the nonequilibrium thermodynamics mechanism proposed in this study, the fluid superheat degree near the wall (t_f - t_{sat}) is the key factor triggering ONB occurrence. To simultaneously reflect the motion characteristic caused by density difference in natural circulation, the dimensionless factor Pr • Gr is used, and dimensionless factor a is introduced as the heat transfer enhancement factor in narrow rectangular channels. The ONB heat flux q_{ONB} in natural circulation narrow rectangular channels can be expressed as a function of (t_f - t_{sat}), Pr • Gr, and a:

[The equation would appear here]

where b = (t_f - t_{sat})/(t_w - t_{sat}); t_f is fluid temperature (ºC); t_{sat} is saturation temperature (ºC); Pr is Prandtl number; Gr is Grashof number; t_w is wall temperature (ºC); and a is the heat transfer enhancement factor in narrow rectangular channels.

5.3 ONB Model Analysis and Test in Natural Circulation Narrow Rectangular Channels

Assuming q_{ONB} = $a(\mathrm{Pr} \cdot \mathrm{Gr})^{m[b(\Delta t_\{sat\})]}$n and based on experimental data from this study [18], the undetermined constants m and n can be solved, yielding the semi-empirical correlation for ONB in narrow rectangular channels under natural circulation:

[The equation would appear here]

The applicable conditions for this equation are: working medium is water, pressure between 0.1 1.5 MPa, mass flow rate between 0 0.025 kg/s, inlet temperature between 10 90ºC, and narrow rectangular channel geometry.

Figure 3 [Figure 3: see original paper] compares calculated values (y-axis) with experimental values (x-axis). Compared with experimental data, the error of calculated ONB values falls within $±$30%. This correlation can be used to predict the required ONB heat flux under experimental conditions. Due to the complexity of ONB occurrence, the data exhibit high dispersion.

6 Influence of Different Factors on ONB in Natural Circulation Narrow Rectangular Channels

6.1 Influence of Wall Superheat Degree on ONB

From the ONB heat flux formulas in Table 1 and the present model, the variation trend of ONB heat flux with wall superheat degree is shown in Fig. 4 [Figure 4: see original paper]. The ONB heat flux increases with growing superheat degree. Yang’s model changes slowly initially, but because the pressure in Fig. 4 is lower than Yang’s experimental pressure, it changes dramatically with superheat degree. At lower superheat degree, Yang Ruichang's model yields the smallest heat flux, but as superheat degree increases, its heat flux grows gradually and eventually exceeds other models. The present model predicts higher ONB heat flux than both Bergles & Rohsenow and Kandlikar's models under the same conditions. At lower superheat degree, the present model's heat flux is higher than Gang's, but with increasing wall superheat degree, the present model's heat flux becomes lower than Gang's, with the present model showing slower variation.

The different trends shown in Fig. 4 arise from different channel types. Comparing Gang Hong's model with the present model reveals that the present model predicts lower ONB heat flux at the initial stage, indicating that ONB occurs more readily in natural circulation. Based on the nonequilibrium thermodynamics and superheat degree mechanism proposed in Section 3, fluid superheat degree is the trigger factor for ONB. However, heating power influences superheat degree through combined action. Heating power is the original cause of natural circulation, representing the source of fluid energy storage and the incentive for superheated fluid. Higher heating power leads to higher superheat degree and earlier ONB appearance. Clearly, ONB in natural circulation appears earlier than in forced circulation under identical conditions.

Heating power is the leading control factor in natural circulation, producing larger density differences than in forced circulation, which weakens heat transfer capability in natural circulation. With slight increases in heat flux, wall temperature may rise rapidly, becoming higher than in forced circulation and leading to higher superheat degree. Therefore, in later stages, Gang's model calculates higher heat flux than the present model.

6.2 Influence of System Pressure on ONB

When internal bubble pressure exceeds fluid pressure, bubbles will grow. Only under this condition will internal bubble pressure perform work, converting mechanical energy into fluid kinetic energy and enabling bubble growth. Figure 5 [Figure 5: see original paper] shows the influence of system pressure on ONB heat flux.

As shown in Fig. 5, ONB heat fluxes computed by Bergles & Rohsenow and Kandlikar's models increase with system pressure, while Gang's model shows decreasing heat flux. The present model shows gentle changes, while Yang's model changes gradually with lower initial heat flux but increases rapidly with pressure growth.

System pressure has dual effects on ONB. On one hand, increased pressure raises thermal resistance, causing gathered local heat to increase boiling nucleation sites, promoting earlier bubble occurrence at lower heat flux. On the other hand, pressure increase reduces density difference, making bubble growth and departure from the heating wall more difficult, lengthening the heating process and delaying bubble occurrence to higher heat flux. In Bergles & Rohsenow and Kandlikar's models, increased system pressure restrains bubble growth, and rising system pressure increases fluid saturation temperature, reducing fluid superheat degree and delaying ONB. In Gang's and the present models, pressure does not directly influence density parameters, as both experiments were conducted at normal pressure. Consequently, Gang's model shows decreasing heat flux with pressure, while the present model changes gently. Yang's experiment was conducted at 7 22.1 MPa, where pressure directly influences latent heat of vaporization and greatly affects dryness, leading to substantial ONB heat flux changes.

6.3 Influence of Inlet Subcooling Degree on ONB

The influence of inlet subcooling degree on ONB heat flux is shown in Fig. 6 [Figure 6: see original paper]. With increasing inlet subcooling degree, ONB heat flux computed by models in Table 1 increases, but the amplitude is large in Yang's model, differing by orders of magnitude from others.

The reason is that only when bubble interface temperature is lower than surrounding fluid temperature will heat transfer to the bubble and vaporize at the interface. Therefore, lower inlet subcooling degree facilitates ONB occurrence. Under otherwise identical conditions, increased subcooling degree makes fluid temperature relatively low at the same position, hindering bubble vaporization and restraining ONB. In natural circulation flow structure, velocity couples with heating. As heat quantity increases, total flow increases. Heating significantly reduces mass velocity in the boundary layer, with higher boundary layer temperatures causing more significant mass velocity reduction. Due to boundary layer effects, flow velocity in the channel center increases obviously, making the bullet-like parabolic velocity distribution more gentle than in forced circulation. Consequently, velocity differences in the fluid velocity boundary layer increase. Therefore, Bergles & Rohsenow and Kandlikar et al.'s models show larger increases than the present model, meaning ONB occurs earlier in natural circulation than in forced circulation under the same conditions.

Additionally, although Yang's model, like the present model, studies natural circulation, its research object is annular channels. The narrow rectangular channel features and secondary flow effects in this study cause earlier ONB occurrence than in annular channels. Yang's experiment was conducted at 7 22.1 MPa, where pressure directly influences latent heat of vaporization and greatly affects dryness. In this study, pressure ranges from 0.1 3.4 MPa, causing significant differences between Yang's model and other models.

6.4 Influence of Non-condensable Gas and Wall Roughness on ONB

On the wall surface, certain size nicks and reentrant cavities exist. These tiny reentrant cavities capture non-condensable gas, steam, or other impurities. Channel fluid cannot be absolutely pure and contains some non-condensable gas or impurities. These wall surface reentrant cavities or impurities may serve as bubble nucleation centers [20], as shown in Fig. 7 [Figure 7: see original paper].

In Fig. 7, 1, 2, 3 represent different size nucleation sites. As Fig. 2 indicates, growing bubbles must reach the growth temperature curve ΔT_g. In Fig. 7, wall roughness follows 1 > 2 > 3, with corresponding wall superheat degrees ΔT_1 = T_{g1} - T_{sat}, ΔT_2 = T_{g2} - T_{sat}, ΔT_3 = T_{g3} - T_{sat}. Fig. 7 shows T_{g1} < T_{g2} < T_{g3}, so $\Delta T_1 < \Delta T_2 < \Delta T_3$, meaning rougher walls facilitate easier ONB occurrence. If non-condensable gas exists in bubbles, steam partial pressure decreases, allowing bubbles to reach critical state with lower heat absorption. Non-condensable gas and wall roughness can reduce the required superheat degree for phase change and make fluid easier to reach nonequilibrium state, thus facilitating ONB occurrence.

7 Conclusion

Based on nonequilibrium thermodynamics and fluctuation theory, the formula for ONB limit superheat degree is proposed. According to nonequilibrium thermodynamics and dissipation theory, the occurrence mechanism and computational model for ONB in narrow rectangular channels under natural circulation are established, with computed results verified by experiment. Finally, ONB features in narrow rectangular channels under natural circulation are analyzed. The summary of our work is as follows:

(1) ONB occurrence is induced by the degree of superheat. Larger heating power produces larger superheat degree, causing earlier ONB occurrence, though still influenced by external environment.

(2) Compared with forced circulation, fluid in natural circulation enters nonlinear stages far from equilibrium earlier, reducing the fluid's evaporation threshold temperature and leading to earlier density fluctuations and ONB occurrence.

(3) Narrow rectangular channels produce secondary flow effects. Compared with conventional channels, the system enters nonlinear stages earlier, fluid near the wall enters superheat state earlier, and narrow rectangular channels lead to earlier density fluctuations.

(4) With increasing pressure, ONB occurs later. Larger inlet subcooling degree delays ONB occurrence. Presence of non-condensable gas in the system and rough wall surfaces facilitate ONB occurrence.

Note: Figure translations are in progress. See original paper for figures.

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