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# Analysis of flow instabilities in forced-convection steam generator

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**Abstract** Because of the practical importance of two-phase instabilities, substantial efforts have been made to date to understand the physical phenomena governing such instabilities and to develop computational tools to model the dynamics. The purpose of this study is to present a numerical model for the analysis of flow-induced instabilities in forced-convection steam generator. The model is based on the assumption of homogeneous two-phase flow and thermodynamic equilibrium of the phases. The thermal capacity of the heater wall has been included in the analysis. The model is used to analyze the flow instabilities in the steam generator and to study the effects of system pressure, mass flux, inlet temperature and inlet/outlet restriction, gap size, the ratio of $d_o/d_i$, and the ratio of $q_i/q_o$ on the system behavior.

**Key words** Steam generator; Forced convection; Flow instability

**CLC numbers** TL33, TK229.92+4

## 1 Introduction

Flow instability appears in a number of two-phase boiling systems, such as reactors, various chemical-process equipments, and phase-change heat exchangers. Steam generators applied in nuclear plant may lead to high-quality density-wave instabilities under some conditions. Oscillations of the flow rate and system pressure are undesirable as they can cause mechanical vibrations, high pressures, and problem of system control, and in extreme circumstances can disturb the heat-transfer characteristics, which may cause the heat- transfer surface to burn out. It is essential, therefore, that such instabilities be avoided or controlled. So, it is important to study the flow instabilities in a forced-convection steam generator.

In the recent years, substantial efforts have been made to date to understand the physical phenomena governing such instabilities [1-4]. Boure *et al*. [5] made a clear classification of flow instabilities. Most of these instabilities mentioned by Boure are concerned with forced circulation, and the density-wave instabilities were concerned with high-steam quality for the BWR conditions. Ishii [6] presented a simplified analytical criterion for the linear stability of a boiling channel for homogeneous and drift-flux models, and established the phase-change number $N_{pch}$ (i.e. the Zuber number $N_{zu}$) and the subcooling number $N_{sub}$ as the most important nondimensional parameters that define the stability of a boiling system. Fukuda and Kobori [7] studied both low- (type I) and high-steam quality (type II) density-wave instabilities for both natural and forced circulation. Achard *et al.* [8] used a distributed parameter homogeneous equilibrium model (HEM) to perform linear stability and dynamic bifurcations analysis. Both supercritical and subcritical Hopf bifurcations were found. Lahey and Podowski [9] presented a general analysis of the dynamics of two-phase flows and illustrated this approach using a boiling channel. Clausse and Lahey [10] presented a nodal, lumped parameter HEM model with moving nodal boundaries on the basis of a Galerkin nodal approximation of the conservation equations for a boiling channel, and, by numerically integrating the modal equations, they found limited cycles and chaotic os-

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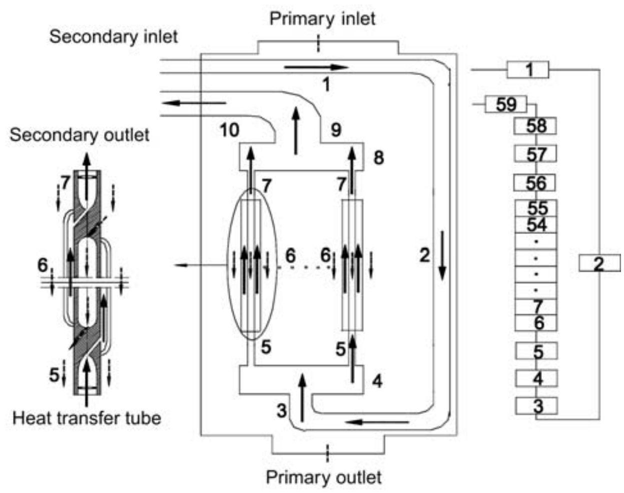
cillations.

Several studies have been made on round tubes or rod bundles; however, the available articles for one-through steam generator (OTSG) under forced convection are very limited. The purpose of this study is to present a numerical model for the analysis of density-wave oscillations of boiling two-phase flow in OTSG. The model is based on the assumption of homogeneous two-phase flow and thermodynamic equilibrium of the phases. The thermal capacity of the heater wall has been included in the analysis. The model is used to analyze the flow instabilities in steam generator and to study the effects of system pressure, mass flux, inlet temperature and inlet/outlet restriction, gap size, the ratio of $d_o/d_i$, and the ratio of $q_i/q_o$ on the system behavior.

## 2 System apparatus

A PWR consists of two loops, primary loop and secondary loop. Steam generator is a key component assembly with which heat is transferred from primary loop to secondary loop to generate a high-temperature superheated steam. So, its reliability is vital for the safety of the nuclear plant.

Steam generators that are used in nuclear plant is shown schematically in Fig. 1. Heat-transfer tubes are annular tubes. Primary hot fluid flows downward, one flow being inside the tube and the other being outside the tube. Secondary cold fluid that flows upward absorbs heat within the steam generator and is transformed to superheated steam at the outlet. It flows in the annular tube. The node sketch corresponding to the computational model is given in the right section of Fig.1.




1,2,3—feed water pipe; 4—inlet plenum;5,7—tube; 6—heat transfer tube; 8—outlet plenum; 9,10—steam exit pipe

**Fig.1** Schematic of a steam generator.

## 3 Mathematical formulation

### 3.1 Fundamental equations

(1) Continuity:

$$\frac{\partial \rho}{\partial \tau}+\frac{\partial}{\partial z}(G)=0 \tag{1}$$

(2) Momentum:

$$\frac{\partial G}{\partial \tau}+\frac{\partial}{\partial z}\left(\frac{G^2}{\rho}\right)+\frac{G^2 f}{2\rho d}+\rho g+\frac{\partial P}{\partial z}+\frac{\xi G^2}{2\rho l}=0 \tag{2}$$

(3) Energy:

$$\frac{\partial(\rho h)}{\partial \tau}+\frac{\partial}{\partial z}(Gh)=\frac{q_l}{A} \tag{3}$$

(4) Wall conduction function:

$$C_p M\frac{\partial T_w}{\partial \tau}=Q_{in}-Q_f \tag{4}$$

$$Q_f=\alpha A_h\left(T_w-T_f\right) \tag{5}$$

(5) State function:

$$\rho=f(P,h) \tag{6}$$

### 3.2 Initial condition and boundary condition

(1) Initial condition:

Initial results are steady-state results that are obtained from an energy balance of the heater itself.

$$T_w(0)=T_{w0} \tag{7}$$

$$G(0)=G_0 \tag{8}$$

(2) Boundary condition:

Constant inlet liquid temperature and constant pressure drop between inlet and exit are assumed.

$$T_{in}(t)=T_{in0} \tag{9}$$

$$P_{in}(t)-P_{ou}(t)=P_{in0}-P_{ou0} \tag{10}$$

### 3.3 Friction coefficient

$$f = \begin{cases} 64/Re & (Re < 1000) \\ 0.048 & (1000 \le Re \le 2000) \\ 0.3164/Re^{0.25} & (Re > 2000) \end{cases} \tag{11}$$

$$Re = Gd/\mu \tag{12}$$

$\mu$ is gained according to quality $x$:

$$x = (h - h_l)/(h_v - h_l) \tag{13}$$

$$\begin{cases} \dfrac{1}{\mu} = \dfrac{1-x}{\mu_l} + \dfrac{x}{\mu_v} & 0 \le x \le 1 \\ \mu = \mu_f & x < 0 \text{ or } x > 1.0 \end{cases} \tag{14}$$

### 3.4 Heat-transfer coefficient

Secondary cold fluid that flows upward absorbs heat within the steam generator and is transformed to subcooled water at the inlet, and the subcooled water is transformed to superheated steam at the outlet. It is divided into four regions: single-phase water, nucleate boiling, film boiling, and single vapor (subcooled boiling is neglected). The division of four regions and the heat-transfer coefficient in each region is as described in Ref. [11].

## 4 Discussion

The mechanism of the density-wave oscillations is described as follows: high-density and low-density steam-water mixture passes through the exit of the system alternately. Fig. 2 shows the simplified system of density-wave oscillations. Pressure at the inlet and the exit of the system is constant. In the case of a small perturbation, for example, $t=0$, a small increase in the inlet mass flux; $t=t_1$, fluid enters the heater section; $t=t_2$, it passes the exit of the heater; $t=t_3$, it enters the exit restriction valve. $\Delta t$ (equal to $t_1+t_2+t_3$) denotes the length of time that the fluid passes through the system. At $t=\Delta t$, low-density steam–water mixture passes the exit restriction valve, exit pressure increases a little, then $P_o$ is larger than the steady-state's result. The growing pressure $P_o$ is transferred to the inlet with velocity of sound. So, $(P_1-P_o)$ decreases, inlet mass flux decreases a little. With another $\Delta t$ delay, high-density steam-water mixture passes the exit restriction valve, exit pressure decreases a little, and then $P_o$ decreases and $(P_1-P_o)$ increases. So inlet mass flux increases a little. This is a period of density-wave oscillations, approximately equal to double the time the fluid passes through the system.

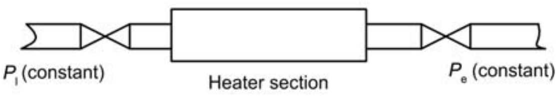



**Fig. 2** Simplified system of density-wave oscillations.

Fig.3 shows a typical density-wave oscillation with $P=7.0$ MPa, $\triangle T_{sub}= 220°C$, and $Q=9.54$ kW. From Fig.3, it is found that the mass flux oscillation exceeds 6%.

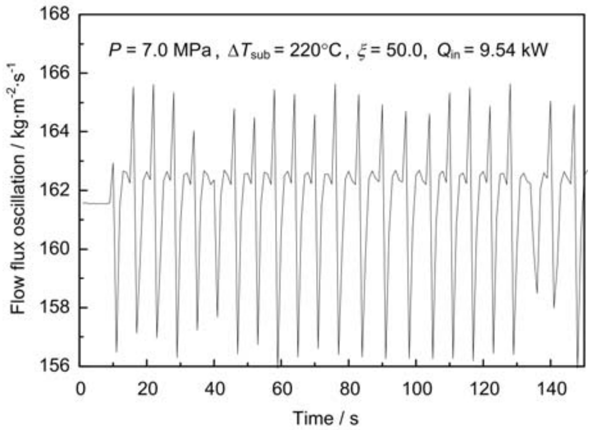



**Fig.3** A typical density-wave oscillation.

### 4.1 Verification of the present model

The present model is modified to facilitate its application in the simulation of the loop in a natural circulation, and on comparison with the results of previous study, the experimental results shows good agreement. Fig. 4 shows the calculation results

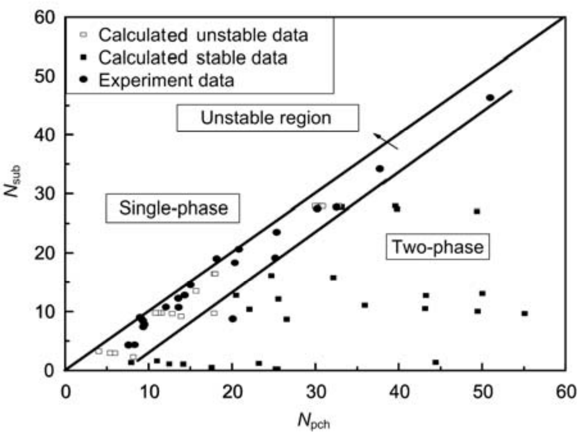



**Fig.4** Comparison of experimental data with computation results.

obtained from the model against experimental data obtained by Su Guanghui [11] in natural circulation. In general, the agreement is very good. Experimental conditions are similar to the practical situation. Hence, it can be concluded that the present model is capable of studying the instability of OTSG.

### 4.2 Steam generator's instability

It is concluded that OTSG is capable of stable operation with the given curve for variant power from 10% FTP to 20% FTP. With tedious calculation, it is also observed that the OTSG is stable if only the exit quality is more than 1.0 (Fig 5). This is attributed to the special inlet design. The inlet mass flux is very large because there are only eight tenuous pipes at the inlet. The feed water pipe is long and there is a prodigious restriction coefficient at the inlet, which leads to friction pressure drop and inlet restriction pressure drop to a large extent. Inlet pressure drop is single phase, and is beneficial to the system's stability.

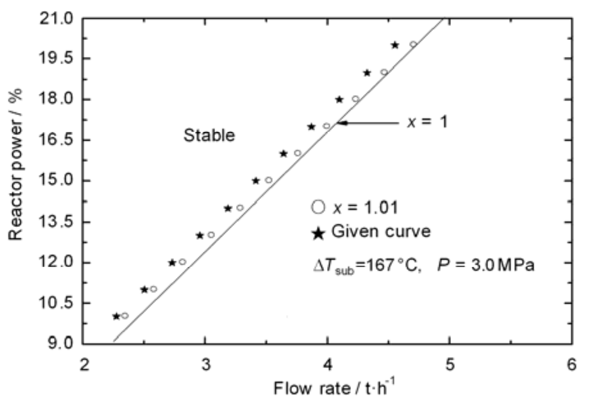
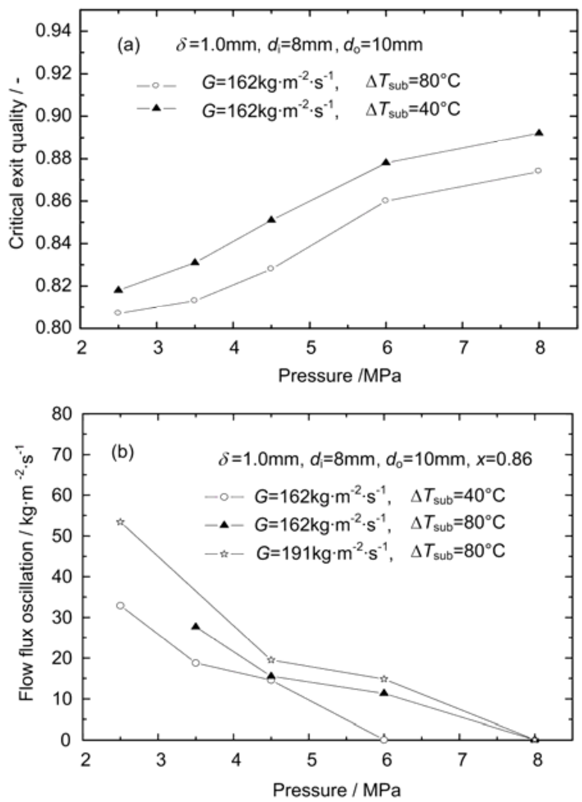



**Fig.5** Steam generator's instability for different power.

### 4.3 Influence of various parameters on instability

#### 4.3.1 Effect of pressure

It is observed from Fig. 6 that the pressure has an effect on density-wave oscillations. Fig. 6 (a) shows the influence with inlet subcooling equal to 40°C and 80°C and mass flux equal to 162.0 kg·m$^{-2}$·s$^{-1}$. It can be concluded that the critical exit quality increases with an increase in pressure, which is beneficial for improving the system's stability. The density difference between the single phase and the two phase decreases with increase in pressure. Under the same conditions, gravity drop perturbation at high pressure is smaller than that at low pressure with equivalent heat input. It is more difficult to generate sustained oscillations at high pressure than at low pressure. Fig. 6 (b) shows the effect of pressure on amplitude of mass flux vibration with the same mass flux, inlet subcooling, and exit quality. It is obvious that the perturbations decay to zero with an increase in pressure.



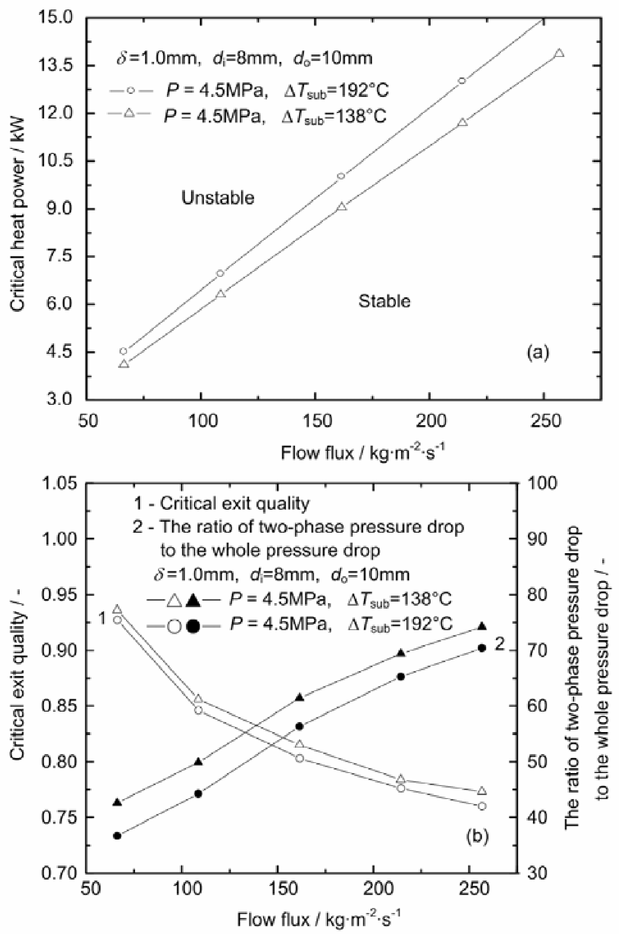

(a) Effect of pressure on critical exit quality;

(b) Effect of pressure on amplitude of mass flux vibration.

**Fig.6** Effect of pressure on instability.

#### 4.3.2 Effect of mass flux

Fig. 7(a) shows critical heat power against mass flux. It is observed that critical heat power increases with increasing mass flux, which is harmful to the system's instability. The reason can be described as follows: the coalescence of bubble is more difficult, and the cooling capacity of the pipe wall is enhanced with increasing mass flux. Two conclusions can be drawn from Fig. 6(b). First, the critical exit quality decreases with increasing mass flux. Hence, density-wave oscillations always occur in the low-quality region with a high mass flux. Second, the ratio of two-phase pressure drop to the whole pressure drop increases with increasing mass flux.




(a) Effect of mass flux on critical heat power;

(b) Effect of mass flux on critical exit quality.

**Fig.7** Effect of mass flux on instability.

### 4.3.3 Effect of inlet subcooling

The inlet subcooling has a considerable effect on the density-wave oscillations. Its influence is complicated and nonlinear, and is linked to two aspects. On the one hand, the length of the single phase increases with increasing inlet subcooling, which is equal to additional inlet restriction pressure drop; so it is beneficial to the system's stability. If this aspect is significant, the influence is single-valued. On the other hand, at the same heat input, average equality decreases and the evaporation time becomes longer with increasing inlet subcooling. The time of inlet mass flow rate corresponding to pressure drop as a result of evaporation becomes shorter, which enhances oscillations. If this aspect is significant, it reduces the system stability with increasing inlet subcooling. In fact, the influence depends on the combined effects of the two aspects. In general, the system stability reduces with increasing inlet subcooling in certain region; the system stability increases with increasing inlet subcooling outside this region. Fig. 8 shows the effect of inlet subcooling on the system instability with a pressure equal to 3.5 MPa, mass flux equal to 190kg·m$^{-2}$·s$^{-1}$ and 253 kg·m$^{-2}$·s$^{-1}$. It is observed that the system stability increases with an increase in inlet subcooling.

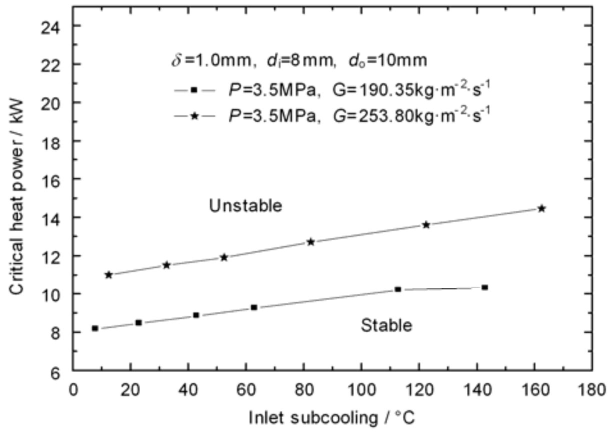



**Fig.8** Effect of inlet subcooling on system instability.

### 4.3.4 Effect of inlet and outlet restriction

According to previous references and experimental data, inlet and outlet restriction has an effect on density-wave oscillations. Increasing inlet restriction is beneficial to the system stability and decreasing inlet restriction will cause damage to the system's stability. But the effect of outlet restriction is on the contrary. It can be concluded from Fig. 9 that the system stability reduces with increasing outlet restriction. With a pressure equal to 4.0 MPa, inlet subcooling equals 150°C, mass flux equals 285 kg·m$^{-2}$·s$^{-1}$, and exit quality equals 0.848, amplitude of mass flux

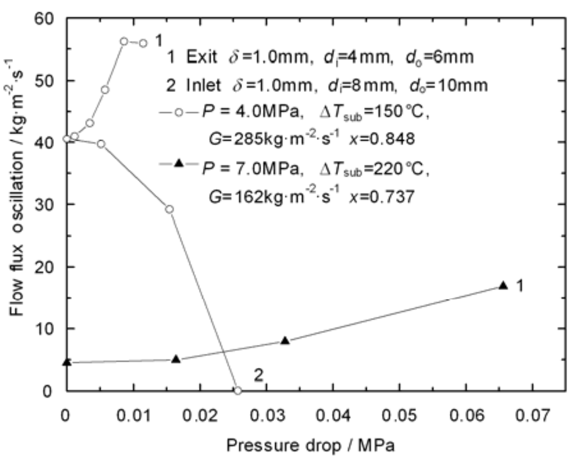



**Fig.9** Effect of restriction on instability.

vibration decreases with an increase in inlet restriction, and amplitude of mass flux vibration increases with an increase in outlet restriction.

**4.3.5** Effect of gap size

The available articles on the analysis of the effect of gap size on the system stability are very limited, and this study is described in this article. Under special operating conditions, with a pressure equal to 4.5 MPa, $d_i$ = 8.0 mm, inlet subcooling equal to 192°C, and mass flux equal to 214.4 kg·m$^{-2}$·s$^{-1}$, it is found that the gap size has an effect on density-wave oscillations. From Fig.10, the effect of gap size is complicated and nonlinear. With the gap size increasing, critical exit quality decreases first, and then increases; however, critical heat power increases monotonously.

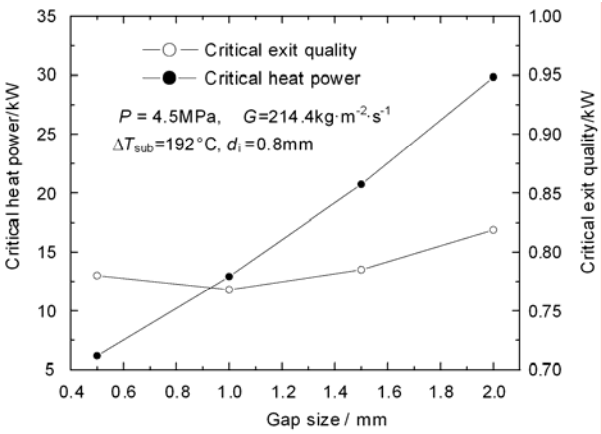


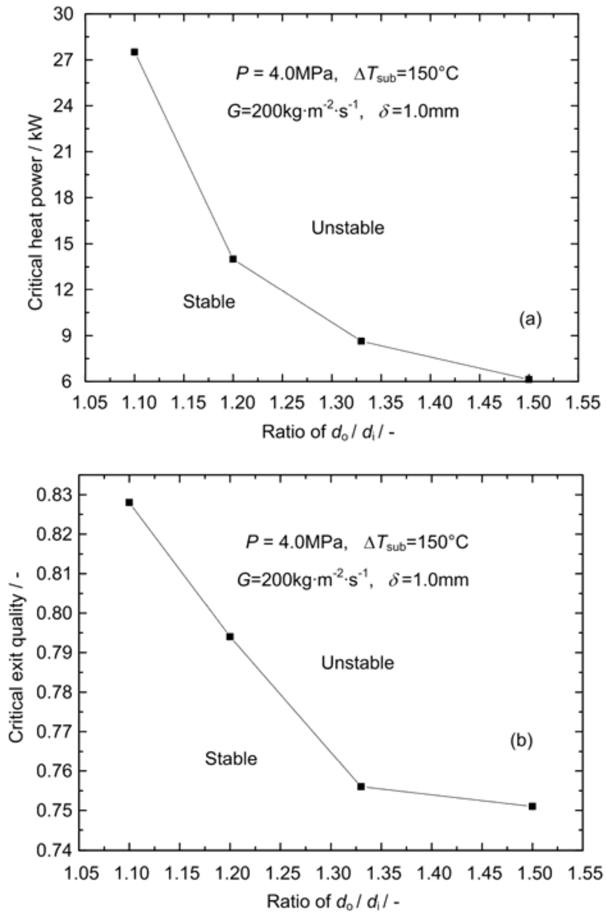

**Fig.10** Effect of gap size on instability.

**4.3.6** Effect of the ratio of $d_o/d_i$

At the same gap size and under similar other conditions, the effect of the ratio of $d_o/d_i$ on instability has never been presented; the same effect is described in this article. It is found that the ratio of $d_i/d_o$ has an effect on density-wave oscillations. From Fig. 11, the critical heat power and critical exit quality decrease with the increase in ratio of $d_o/d_i$, with pressure equal to 4.0MPa, $\delta$ = 1.0 mm, inlet subcooling equal to 150°C, and mass flux equal to 200kg·m$^{-2}$·s$^{-1}$.

**4.3.7** Effect of the ratio of $q_i/q_o$

With tedious calculation, it is observed that the ratio of $q_i/q_o$ did not influence the system instability for the same heat power.




(a) Effect of the ratio of $d_o/d_i$ on critical heat power;

(b) Effect of the ratio of $d_i/d_o$ on critical exit quality.

**Fig.11** Effect of the ratio of $d_i/d_o$ on instability.

## 4.4 Instability region

The thermal-hydraulic instability of a two-phase forced-convection circulation is a very complex multivariable and nonlinear system. Factors such as mass flux, heat power, and loop structure interact with each other. So, all the factors have to be taken into account. In this study, dimensionless phase change ($N_{pch}$) and subcooling number ($N_{sub}$) that synthetically consider influencing factors are adopted to describe the instability region. From Fig. 12, the instability region is a slender region. The flow oscillation may occur in this region of OTSG. It is essential, therefore, that OTSG be avoided to run in this region.

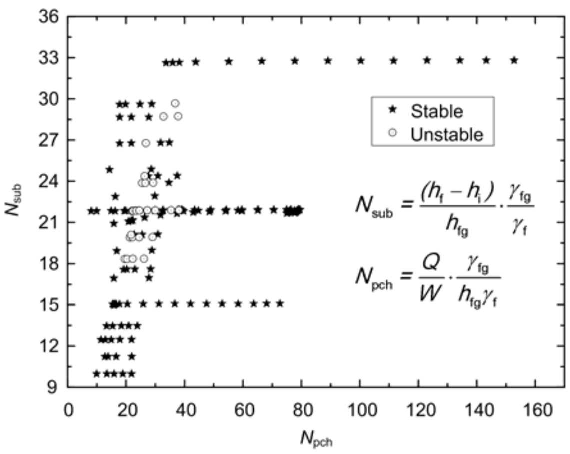



**Fig.12** Instability region described with subcooling number ($N_{sub}$) and phase change ($N_{pch}$).

## 5 Conclusions

A new homogeneous phase equilibrium model is described in this article. The model is used to analyze the flow instabilities in the steam generator, and to study the effects of system pressure, mass flux, inlet temperature and inlet/outlet restriction, gap size, the ratio of $d_o/d_i$, and the ratio of $q_i/q_o$ on the system behavior. With tedious calculation, the following conclusions can be drawn.

(1) OTSG is capable of stable operation for variant power from 10% FTP to 20% FTP if only superheated steam exists at the exit.

(2) An increase in pressure is beneficial to the system's stability. Critical exit quality increases with increasing pressure.

(3) High-mass flux is accompanied by high-critical heat power and low-critical exit quality.

(4) Inlet subcooling has a complicated and nonlinear effect on the system's stability. But in this study, it is observed that the system's stability increased with an increase in inlet subcooling.

(5) Increasing inlet restriction is beneficial to the system's stability; however, an increase in outlet restriction reduces the system's stability.

(6) With the increase in gap size, critical exit quality decreases first, and then increases; however, critical heat power increased monotonously.

(7) Critical heat power and critical exit quality decreased with the ratio of $d_o/d_i$ increasing for the same gap size.

(8) The ratio of $q_i/q_o$ has no influence on the system's instability for the same heat power.

(9) Flow instability region described with subcooling number ($N_{sub}$) and phase change ($N_{pch}$) is a slender region. OTSG may present flow oscillation in this region. It is essential, therefore, that OTSG be avoided to run in this region.

### Nomenclature

| | |
|---|---|
| $P$ | Pressure (Pa) |
| $G$ | Mass flux ($kg \cdot m^{-2} \cdot s^{-1}$) |
| $\tau$ | Time (s) |
| $T$ | Temperature (K) |
| $\Delta T_{sub}$ | Inlet subcooling |
| $Q_f$ | Heat absorbed by fluid (W) |
| $Q_{in}$ | Heat transferred to wall (W) |
| $q_l$ | Heat per unit length ($W \cdot m^{-1}$) |
| $z$ | Axial coordinate (m) |
| $d$ | Diameter (m) |
| $f$ | Friction coefficient (dimensionless) |
| $h$ | Enthalpy ($kJ \cdot kg^{-1}$) |
| $C_p$ | Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$) |
| $M$ | Wall mass (kg) |
| $A$ | Flow area ($m^2$) |
| $A_h$ | Surface heat area ($m^2$) |
| $x$ | Quality (dimensionless) |
| $Re$ | Reynolds number (dimensionless) |
| $N_{pch}$ | Phase-change number (dimensionless) |
| $N_{sub}$ | Subcooling number (dimensionless) |

### Greek symbols

| | |
|---|---|
| $\rho$ | Density ($kg \cdot m^{-3}$) |
| $\alpha$ | Heat-transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$) |
| $\mu$ | Viscosity coefficient ($N \cdot s \cdot m^{-2}$) |
| $\xi$ | Local resistance coefficient (dimensionless) |
| $\delta$ | Gap size (mm) |

### Subscripts and superscripts

| | |
|---|---|
| i | Inside tube |
| o | Outside tube |
| in | Inlet |
| ou | Exit |
| w | Wall |

f Liquid

l Saturated water

v Saturated vapor

0 Steady state

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