The Effect of Heater-to-Riser Configuration on the Stability of a Two-Phase Natural Circulation System

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ABSTRACT

Heater and riser are very important parts of a two-phase boiling natural circulation system. The configuration of heater-to-riser may play a key role on how to promote the stability and operating safety of the two-phase flow system. This study extends the simple nonlinear analysis model developed by Lin and Pan [7] to discuss and compare the effects of different heater-to-riser structures on the system stability. The results show the suddenly contraction and nozzle structures have rather poor stability performance by focusing on the stability only. Though the size contraction may have a stable effect on the Type-I instability region, the Type-II instability region is dramatically enlarged and the stable region only exists in a small low power area. On the other hand, the suddenly expansion and diffuser structures possess relatively excellent stability capability. The size enlargement can induce both stable effects on the Type-I and Type-II unstable regions. Moreover, the results indicate that the included angle seems to have a negligible effect on the Type-I unstable region in the nozzle and diffuser systems, while the influence of the included angle on the Type-II instability region may depend on how the form loss coefficient changes with the included angle.

Keywords: two-phase flow, natural circulation, stability

加熱段至升流段組成結構對雙相自然循環系統穩定性的影響

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摘　　要

加熱段與升流段是雙相流自然循環系統非常重要的組件，兩者之間組成的幾何結構對於雙相流系統，如何提升穩定與運轉安全，有其關鍵的影響。本文延伸 Lin and Pan [7] 所發展之簡易非線性分析模式，並應用於探討與比較不同加熱段與升流段組成結構對系統穩定性之影響。結果發現瞬間縮小結構與噴嘴結構是較不穩定的結構；雖然對於低功率的 Type-I 不穩定區會有穩定的效應；但會造成 Type-II 不穩定區急遽擴大，致使系統只存在小的低功率穩定區。另一方面，瞬間擴大結構與擴散器結構相較之下是較穩定的結構，對 Type-I 與 Type-II 不穩定性均有穩定之作用。此外，分析結果亦顯示噴嘴與擴散器結構的開口角度變化對 Type-I 不穩定區的影響很小；但會視開口角度大小影響 Type-II 不穩定區。

關鍵詞：雙相流，自然循環，穩定性

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Ⅰ. INTRODUCTION

Since the concern in the safety operation of a boiling water reactor (BWR), the passive feature of natural circulation has been selected as an important heat removal mode for some advanced power systems, i.e. advanced boiling water reactor (ABWR). The passive safety of the two-phase natural circulation system has induced extensive researches in the last decade [1]. Some of them were carried on the test reactors including Dodewaard reactor and European SBWR [2], especially the low-pressure stability issue of such a system.

Type-I and Type-II instabilities are two main well-known types of instability occurring in the two-phase natural circulation system. As reported by Fukuda and Kobori [3], Type-I instability (low quality density-wave instability) exists in the very low power region, which is caused by the gravitational pressure drop. On the other hand, Type-II instability (high quality density-wave instability) appears in the high power region, which is induced by the two-phase frictional pressure loss. As the power level is increased at a particular pressure and inlet subcooling, the stability nature of a two-phase natural circulation system can be divided into Type-I instability region, Type-I stability boundary, stable region, Type-II stability boundary and Type-II instability region from the low power range to the high power range. Because the startup of a nuclear plant located in the low pressure and low power area, it should pay much more attention to the Type-I instability.

Riser (standpipe) is an essential component of a two-phase natural circulation system. The existence of a riser can strengthen the natural circulation and enhance the system flow. Therefore, lengthening the riser could generate a stable influence on the Type-II instability region [4,5]. However, it might destabilize the Type-II instability region in a nuclear-coupled heating system due to the enlargement of two-phase frictional pressure drop [6]. Moreover, the riser was also a key part contributing to the appearance of the Type-I instability [5]. A longer riser enlarged the gravitational pressure drop to expand Type-I unstable region [4-6].

Nonlinear analysis has been a major approach to analyze the stability characteristics of a two-phase boiling system. Lin and Pan [7] extended the approach suggested by Clausse and Lahey [8] to develop a nonlinear model for a boiling channel with riser under natural convection. Their results demonstrated that an oscillating channel could be stabilized by a change of power from the unstable region to the stable region. Lee and Pan [6,9] also developed nonlinear analysis models based on the methodology of Clausse and Lahey [8] to investigate the nonlinear dynamics and stabilities of natural circulation systems with either nuclear heating or multiple parallel boiling channels. They found that a two-phase natural circulation loop might have complex nonlinear phenomena under different operating conditions, especially chaotic oscillations. Some complex analytical codes, such as BifDD [10], were established to provide a deep insight in the nonlinear phenomenon. Their studies showed complex analytical codes could be properly applied to conduct nonlinear analyses against experimental results.

Heater and riser are two major parts of the two-phase boiling circulation system. As author known, the past studies were very deficient in concerning the stability problem of the heater-to-riser structure. Therefore, the present study extends the simple nonlinear analysis model developed by Lin and Pan [7] to investigate the influence of the heater-to-riser formation on the stability of a two-phase natural circulation system.

Ⅱ. THE MODEL

Depending on the geometry size and formation shape between heater and riser, the present research considers four types of the heater-to-riser configuration as displayed in Fig. 1. The figure says: (A) suddenly expansion; (B) suddenly contraction; (C) gradually expansion (diffuser) and (D) gradually contraction (nozzle). While investigating the influence of the heater-to-riser formation on the system stability, the simplified natural circulation loop is comprised of heater, riser and downcomer. Notably, in order to consider the effect of formation type, each configuration consisting of heater and riser in Fig. 1 has the same total length.

By adopting the homogeneous two-phase flow model, the conservation equations for each component of this natural circulation system can be written in the following non-dimensional forms for either single- or two- phase regions:

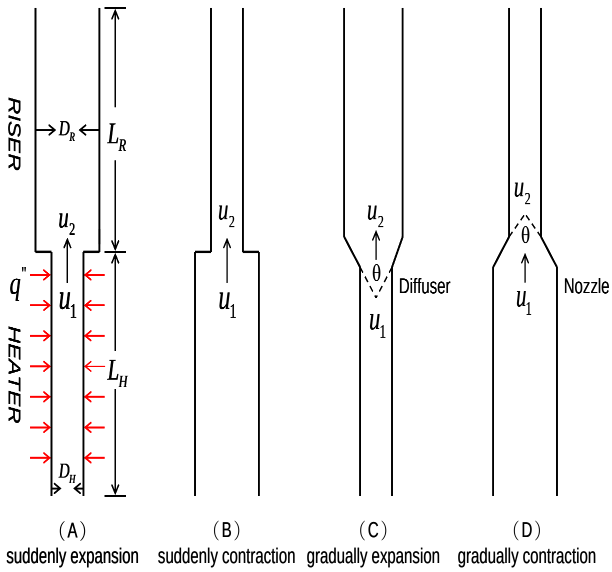

Fig. 1. The fundamental formation types of the heater-riser system.

$$\frac{\partial \rho^+}{\partial t^+} + \frac{\partial \rho^+ u^+}{\partial z^+} = 0 \tag{1}$$

$$\frac{\partial \rho^+ h^+}{\partial t^+} + \frac{\partial \rho^+ h^+ u^+}{\partial z^+} = q'''^+ \tag{2}$$

$$\frac{\partial \rho^+ u^+}{\partial t^+} + \frac{\partial \rho^+ {u^+}^2}{\partial z^+} = -\frac{1}{Fr}\frac{\partial P^+}{\partial z^+} - \frac{fL_H}{2D}\rho^+ {u^+}^2$$
$$-\sum_{m=1}^{N} k_m \delta\left(z^+ - z_m^+\right)\frac{\rho^+ {u^+}^2}{2} - \frac{\rho^+}{Fr} \tag{3}$$

The last term in Eq. (2), q'''^+, is set to zero except for the heater.

The following assumptions are made to simplify the problem:

(1) Constant properties at the system pressure are used under both steady and dynamic conditions,

(2) The heat flux is assumed to be uniform in the axial direction of the heater section,

(3) The channel keeps at a constant inlet subcooling during dynamic analysis,

(4) Subcooled boiling is not considered; and,

(5) The flashing effect in the riser is neglected at this high-pressure system.

The present analytical model is extended by the methodology of Lin and Pan [7] on the basis of Galerkin nodal approximation [8]. The single phase region inside the heater is divided into N_s spatial nodes with equal enthalpy change. The non-dimensional governing equations are integrated by assuming linear enthalpy profile between neighboring nodes. The location of each node is changed dynamically with a moving boiling boundary ($\lambda(t)$). For a steady state, the non-dimensional boiling boundary, $\lambda^+ = N_{sub} u_{i0}^+ / N_{pch}$, depends on the steady state flow velocity (u_{i0}) at a given heat flux and inlet subcooling. Furthermore, the two-phase region of heater is treated as one node and the two-phase riser is discretized into N_R spatial nodes with fixed positions and identical length. The non-dimensional governing equations in the riser can be further integrated by assuming the linear quality distribution between each node. The detail model is discussed in Lin and Pan [7] and will not be re-mentioned here. If only consider the gravitational pressure head in the downcomer section, the system is subjected to a constant total pressure drop. The relation can be drawn in the following non-dimensional equation:

$$\Delta P_H^+ + \Delta P_R^+ = 1 + L_R^+ \tag{4}$$

Substituting Eq. (18)-(22) in Lin and Pan [7] into Eq. (4) and after some rearrangements, the non-dimensional dynamic equation of inlet velocity at the heater can be given:

$$\frac{du_i^+}{dt^+} = \left[\left(1 + L_R^+\right) - \Delta P_{H0}^+ - \Delta P_{R0}^+\right]$$
$$/\left[Fr\left(M_{ch}^+ + M_R^+ / {A_R^+}^2\right)\right] \tag{5}$$

Where,

$$\Delta P_{H0}^{+} = Fr[u_i^{+} - N_{pch}(1-\lambda^{+})]\frac{dM_{ch}^{+}}{dt^{+}}$$
$$- Fr\frac{(1-M_{ch}^{+})}{(1/\rho_e^{+}-1)}N_{pch}\frac{d\lambda^{+}}{dt^{+}}$$
$$+ Fr\frac{N_{pch}(1-\lambda^{+})(1-M_{ch}^{+})}{(1-\rho_e^{+})^2}\frac{d\rho_e^{+}}{dt^{+}}$$
$$+ N_{\exp}N_{sub}\left[\lambda^{+} - \frac{1}{2N_s}\sum_{n=1}^{N_s}(2n-1)\left(L_n^{+} - L_{n-1}^{+}\right)\right]$$
$$+ M_{ch}^{+} + Fr(\rho_e^{+}u_e^{+^2} - u_i^{+^2}) + \Lambda_{1\phi}Fr\lambda^{+}u_i^{+2}$$
$$+ \Lambda_{2\phi}Fr\left\{\frac{1-\lambda^{+}}{1/\rho_e^{+}-1}u_i^{+2}\ln(1/\rho_e^{+}) + \frac{2u_i^{+}N_{pch}(1-\lambda^{+})(1-M_{ch}^{+})}{(1/\rho_e^{+}-1)}\right.$$
$$+ \left[N_{pch}(1-\lambda^{+})/(1/\rho_e^{+}-1)\right]^2 \times$$
$$\left.\left[\frac{1}{2}(1/\rho_e^{+}-3)(1-\lambda^{+}) + M_{ch}^{+} - \lambda^{+}\right]\right\}$$
$$+ Fr(\frac{1}{2}k_i u_i^{+2} + \frac{1}{2}k_e\rho_e^{+}u_e^{+2}) \qquad (6)$$

And,

$$\Delta P_{R0}^{+} = -Fr\frac{M_R^{+}}{A_R^{+^2}}N_{pch}\frac{d\lambda^{+}}{dt^{+}} + Fr\frac{u_R^{+}}{A_R^{+}}\frac{dM_R^{+}}{dt^{+}}$$
$$+ Fru_R^{+2}(\rho_{NR}^{+} - \rho_e^{+}) + Fr\frac{\Lambda_R}{A_R^{+}L_R^{+}}M_R^{+}u_R^{+2}$$
$$+ M_R^{+}/A_R^{+} + \frac{1}{2}Frk_{\mathrm{Re}}\rho_{NR}^{+}u_R^{+^2} \qquad (7)$$

The effect of heater-to-riser structure on the form loss is included in the form loss coefficient at the heater exit, k_e, as in the last term of Eq. (6).

Ⅲ. SOLUTION METHOD

Before the numerical procedure is proceeded, it must choose one of fundamental types in Fig. 1 as the analytical case. Based on the dimensions of heater diameter (D_H) listed in Table 1, the parameter values of diameter ratio (D_R / D_H) can be given following what is the selected type of the heater-to-riser configuration. Furthermore, the form loss coefficient at the outlet of the heater (k_e) can be determined instantaneously.

After the geometry parameter of the selected case is set, the steady state characteristics of the natural circulation system depend on the heating power and inlet subcooling of the heater. By setting the time-derivative terms of the dynamic equations to zero, it will result in a set of nonlinear algebraic equations for the steady state of the system. This work applies the subroutine SNSQE of Kahaner et al. [11], which employs the Powell Hybrid scheme, to solve for the steady state. The transient responses of this system following a perturbation at a given initial steady state can be determined by solving the set of nonlinear, ordinary differential equations. This numerical analysis can be completed by the subroutine SDRIV2 of Kahaner et al. [11], which employs the Gear multi-value method.

Table1. The geometries and normal operating conditions of an ABWR based on the data of Preliminary Safety Analysis Report [12]

Heater	P	72.7 bar
	Q	3926 MWt
	L_H	3.81 m
	D_H	0.01 m
	$f_{1\phi}$	$0.14/\mathrm{Re}^{-0.1656}$
	k_i	42.48
Riser	L_R	1.211 m

Ⅳ. RESULTS AND DISCUSSION

In this study the typical geometries and normal operating conditions are referenced to an ABWR still under construction based on the data of Preliminary Safety Analysis Report [12] as listed in Table 1.

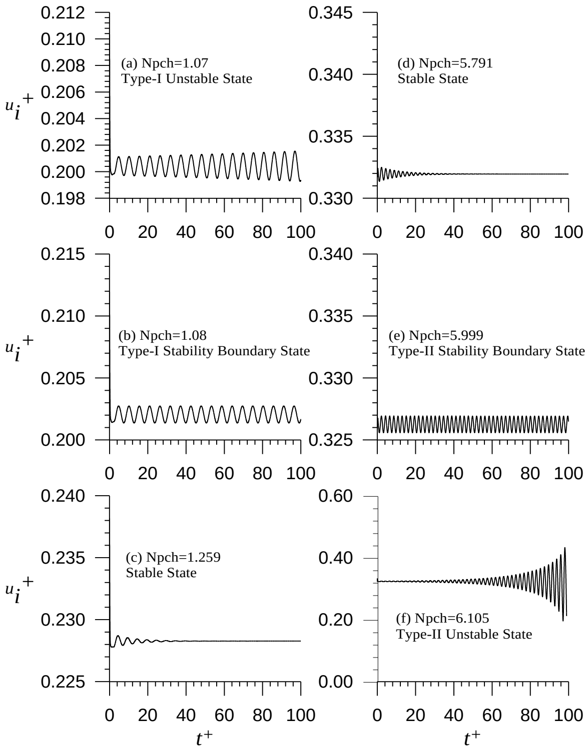

Fig. 2. Transient responses following a perturbation in the inlet velocity of the heater by changing the heating power at $N_{sub} = 4.936$ for a natural circulation ABWR.

4.1 Nonlinear Time Domain Analysis

The effect of heater-to-riser configuration will be investigated by the nonlinear time domain analysis. The nonlinear oscillation characteristics of a two-phase natural circulation system are plotted in Fig. 2. The results display the time evolution of inlet velocity following a perturbation by changing the heating power at a fixed subcooling number ($N_{sub} = 4.936$) for a natural circulation ABWR. Figure 2(a) and 2(f) demonstrate that for a low power state of $N_{pch} = 1.07$ (which corresponds to the Type-I unstable state) and for a high power state of $N_{pch} = 6.105$ (which corresponds to the Type-II unstable state), respectively. The results indicate that the magnitudes of the inlet velocity oscillation grow continuously and thus present two types of unstable oscillation. Figure 2(b) and 2(e) illustrate that for a low power state of $N_{pch} = 1.08$ (which corresponds to the Type-I stability boundary) and for a high power state of $N_{pch} = 5.999$ (which corresponds to the Type-II stability boundary), respectively. The results reveal both of these two states eventually evolve to limit cycle oscillations. Figure 2(c) and 2(d) illustrate two operating states of $N_{pch} = 1.259$ and $N_{pch} = 5.791$, which correspond to a low power stable state and a high power stable state, respectively. The figures show that the oscillations decay quickly and finally stay in the original steady states. Moreover, Fig. 2 also suggests that the high power state possesses a more high oscillation frequency with respect to the low power one.

Table 2. The conditions among the analytical cases of suddenly expansion and suddenly contraction shown in Fig. 1 [13]

Structure	D_R / D_H	k_e	Heater-Riser form loss
suddenly expansion	2.0	0.56	$\frac{1}{2} k_e \rho_e u_1^2$
	4.0	0.88	$k_e =$
	6.0	0.945	$(1 - D_H^2 / D_R^2)^2$
suddenly contraction	0.6	0.269	$\frac{1}{2} k_e \rho_e u_2^2$
	0.5	0.315	$k_e =$
	0.4	0.353	$0.42(1 - D_R^2 / D_H^2)$

*Note that k_e is based on the velocity head in the small pipe.

4.2 The Effect of Suddenly Expansion

Considering the connection between heater and riser is the formation shape of suddenly expansion as shown in Fig. 1, the effect of suddenly expansion structure could be evaluated through nonlinear time domain analysis by step change of diameter ratio (D_R / D_H) from 2.0, 4.0 to 6.0 as listed in Table 2. In addition, the form loss coefficient k_e increases slightly due to the enlargement of the diameter ratio. On the non-dimensional plane of the phase change number (N_{pch}) and the subcooling number (N_{sub}), Fig. 3 compares the influence of three suddenly expansion cases on the stability of the two-phase natural circulation system. In the low power region, at the same operating power enlarging the riser diameter size may lead to the decrease in flow velocity, and thus relatively high void fraction and low gravitational pressure drop. This may stabilize the Type-I instability in the low power region as shown in Fig. 3. In the high power region, the enlargement of diameter ratio can contribute to the two-phase form loss ($k_e \rho u^2 / 2$) . However, the two-phase frictional pressure drop ($\rho u^2 fL / 2D$) can be reduced by the effect of large diameter size (D). In this analytical system, the overall effect of enlarging diameter ratio may lead to the slight reduction in the two-phase frictional pressure drop. Therefore, the results in Fig. 3 indicate that the influence of suddenly expansion can slightly stabilize the system in the Type-II instability region.

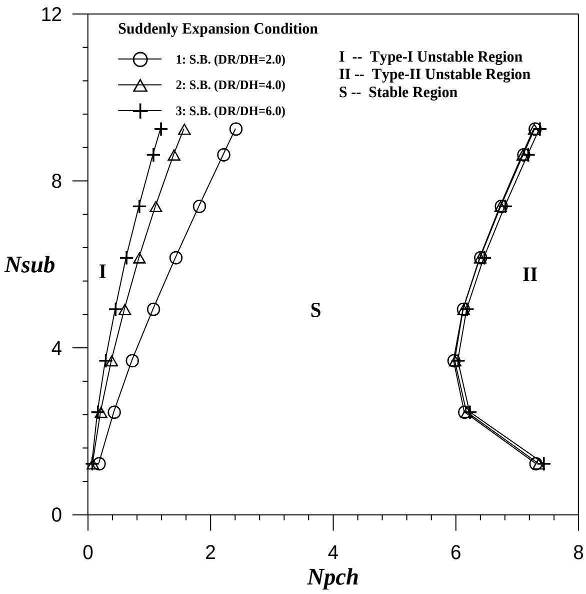

Fig. 3. The effect of the suddenly expansion structure on the stability of the two-phase natural circulation system.

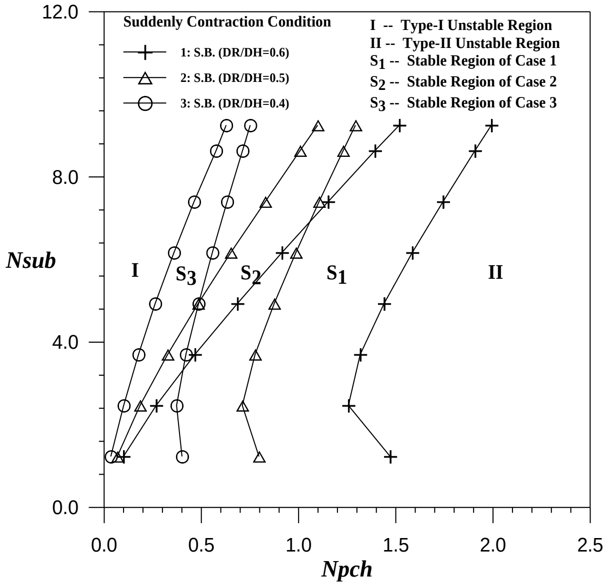

Fig. 4. The effect of the suddenly contraction structure on the stability of the two-phase natural circulation system.

4.3 The Effect of Suddenly Contraction

Following the similar analytical effort, the influence of suddenly contraction structure could be investigated by step change of diameter ratio from 0.6, 0.5 to 0.4 as listed in Table 2. Figure 4 compares different stability maps among these three suddenly contraction cases. Contracting the diameter size could induce the slight increase in the form loss coefficient as displayed in Table 2. Because it is totally two-phase flow inside the riser, the two-phase frictional pressure drop can be dramatically enlarged by the combined effects of size contraction and two-phase form loss. Consequently, the influence of suddenly contraction can significantly destabilize the Type-II instability in the high power region as shown in Fig. 4. The Type-II instability region quickly expands toward the low power area and the stable region only exists in a small low power range. However, in the low power region the flow restriction can be enhanced by suddenly reducing the diameter size. At the same operating power, this effect may induce relatively high void fraction and thus reduce the gravitational pressure drop to stabilize the

Type-I instability as revealed in Fig. 4.

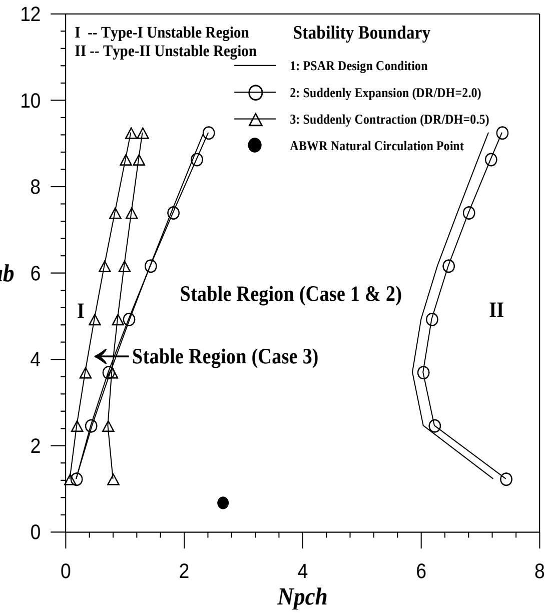

Fig. 5. The comparison among the cases of suddenly expansion and suddenly contraction on the stability of the two-phase natural circulation system.

4.4 The Comparison between Suddenly Expansion and Suddenly Contraction

The comparisons between the cases of suddenly expansion and suddenly contraction are further displayed in Fig. 5. The results show that the suddenly contraction structure ($D_R / D_H = 0.5$) stands a rather poor stability performance; respectively, the suddenly expansion structure ($D_R / D_H = 2.0$) exhibits a more excellent stability capability. The suddenly contraction case is the most unstable one by comparing the stability maps among different analytical cases. The figure suggests the suddenly contraction structure can induce more stable effect on the Type-I instability region but very strong unstable effect on the Type-II instability region with respect to the other cases. In addition, the ABWR natural circulation point is a very stable state in both PSAR design and the suddenly expansion case, however, it will turn into the unstable state in the suddenly contraction system. On the other hand, in the low power region the suddenly expansion structure ($D_R / D_H = 2.0$) and the PSAR design condition ($D_R / D_H = 1.13$) almost have the same Type-I stability boundary, while in the high power region the suddenly expansion structure is more stable than the PSAR design condition. Moreover, a proper design of such system should take the cost of size enlargement and the requirement of other technology into consideration.

Table 3. The form loss coefficients （ k_e ）of Diffuser and Nozzle shown in Fig. 1 [14]

Diffuser	**Included Angle (θ)**					
A_R / A_H	**15**	**30**	**45**	**60**	**90**	**120**
16.67	0.29	0.6	0.84	0.88	0.88	0.88
10	0.28	0.59	0.76	0.8	0.83	0.84
4	0.22	0.46	0.61	0.68	0.64	0.63
2	0.13	0.32	0.33	0.33	0.32	0.31
Nozzle	**Included Angle (θ)**					
A_R / A_H	**15**	**30**	**45**	**60**	**90**	**120**
0.5	0.2	0.2	0.22	0.24	0.48	0.72
0.25	0.64	0.64	0.88	1.1	2.7	4.3
0.167	1.4	1.4	2	2.5	6.5	10

4.5 The Effect of Diffuser Structure

Table 3 lists the form loss coefficients (k_e) of diffuser and nozzle shown in Fig. 1 in response to the area ratios (A_R / A_H) and the included angles (θ) [14].

Figure 6 compares the influence of the included angle on the stability of the diffuser system under two different area ratios（ A_R / A_H =

4.0 and 16.67, respectively）.

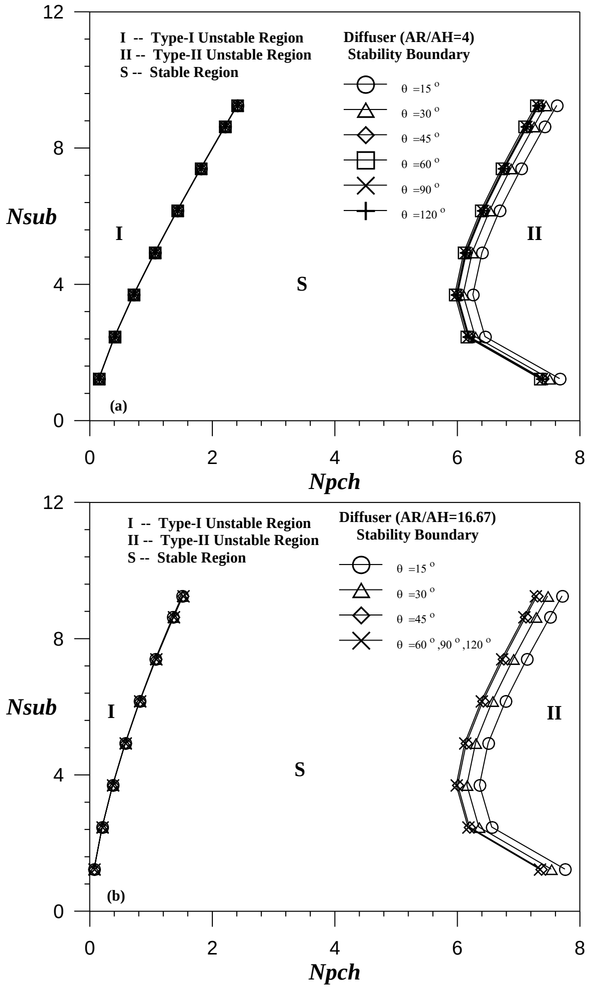

Fig. 6. The effects of the included angle on the stability of a diffuser system under different area ratios: (a) A_R / A_H = 4, (b) $A_R / A_H = 16.67$

In the low power region, the results reveal that the included angle has a negligible effect on the Type-I unstable region. Because this study only considers the impact of the included angle on the form loss, the change in the included angle may lead to the slight change in flow density as well as the gravitational pressure drop at a fixed area ratio. This generates a little effect on the Type-I instability in the present diffuser system subject to a constant total pressure drop. On the other hand, in the high power region the effect of included angle may depend on how the form loss coefficient changes with the included angle. In the small included angle range ($\theta<60^o$), the form loss coefficient increases as the included angle to enlarge the two-phase form loss. This may destabilize the system in the Type-II instability region. However, in the medium-to-large included angle range ($\theta>60^o$), the form loss coefficient is either unchanged ($A_R / A_H = 16.67$) or slightly decreased ($A_R / A_H = 4.0$) as the included angle. This induces a small effect on the system stability in the Type-II instability region.

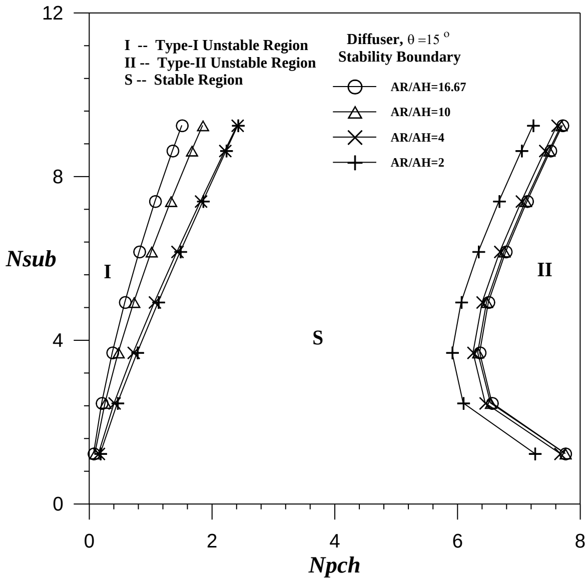

Fig. 7. The effects of the area ratio on the stability of a diffuser system at an included angle $\theta=15^o$.

Figure 7 further evaluates the influence of the area ratio on the system stability at an included angle $\theta= 15^o$. As displayed in table 3, at a fixed included angle, enlarging the area ratio can result in the increase of the form loss coefficient. Thus, the decrease in flow velocity and relatively high void fraction. In the low power region, it would lead to the reduction in the gravitational pressure drop. Therefore, the results in Fig. 7 suggest that the effect of the area ratio has a stable influence on the Type-I instability region. In the high power region, enlarging the area ratio can result in the increase of the form loss coefficient to increase the two-phase form loss. But a large diameter size (D) can also reduce the two-phase frictional pressure drop. In this study the overall effect of the area ratio leads to the reduction in the two-phase frictional pressure drop, Fig. 7 shows that it can have a stable effect on the Type-II instability region.

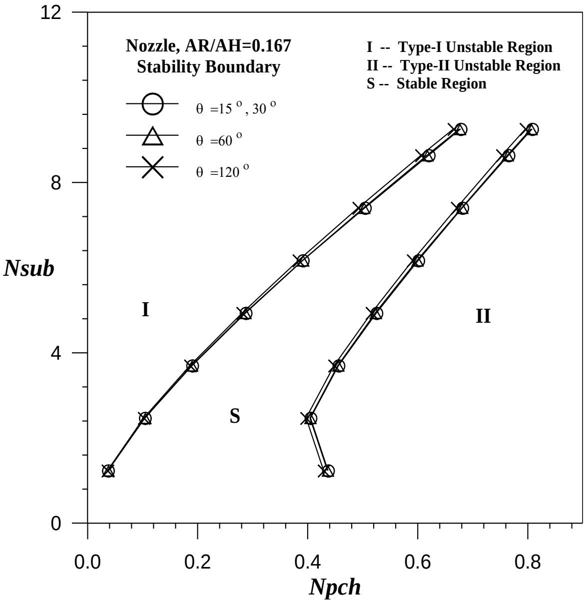

Fig. 8. The effects of the included angle on the stability of a nozzle system at an area ratio A_R / A_H = 0.167.

4.6 The Effect of Nozzle Structure

The form loss coefficients of the nozzle system shown in Fig. 1 depend on the area ratio and included angle as listed in Table 3 [14]. Figure 8 compares the influence of the included angle on the stability of the nozzle system at an area ratio (A_R / A_H = 0.167). The results indicate that the included angle seems to have little effects both on the Type-I and Type-II unstable regions in the nozzle system. This may be described by the relation between the flow velocity and the form loss coefficient corresponding to the change in the included angle. The small included angle (θ=15°; 30°) leads to a small form loss coefficient ($k_e = 1.4$), while the large included angle (θ=120°) induces a large one ($k_e = 10.0$), respectively. However, at the same operating power, the system with a small k_e may result in a high flow velocity with respect to the system with a large k_e. Therefore, the influence of flow velocity and the form loss coefficient could be suppressed by each other in evaluating the two-phase form loss ($k_e \rho u^2 / 2$). In the present analytical system, increasing the included angle only slightly influences the two-phase frictional pressure drop and product a little unstable effect on the Type-II instability.

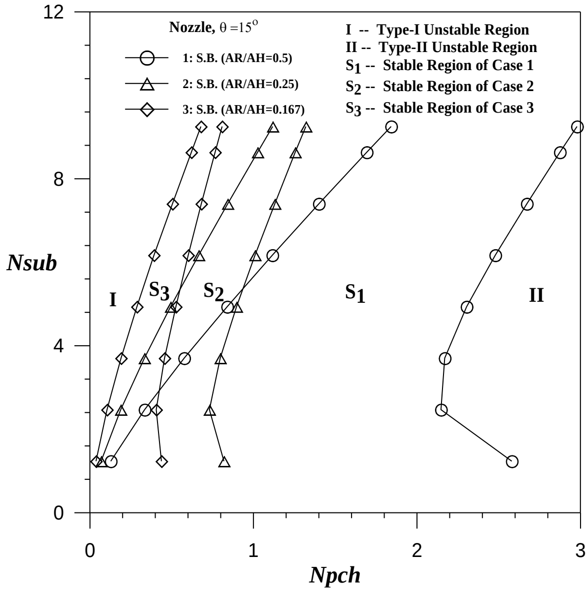

Fig. 9. The effect of the area ratio on the stability of a nozzle system at an included angle θ=15°.

The influence of the area ratio on the nozzle system is evaluated in Fig. 9 at an included angle θ=15°. As displayed in table 3, the form loss coefficients are increased as the contraction of the flow area at a fixed included angle. At the same operating power, the contraction of area size may cause a low flow rate as a result of the increase in flow restriction; comparatively leads to a high void fraction and a low gravitational pressure drop in the low power region. Thus, the contraction of flow area may have a stable effect on the Type-I instability region as shown in Fig. 9. In the high power region, the two-phase frictional pressure drop can be greatly enlarged by both the reduction of diameter size (D) and the increase of form loss (k_e) as the contraction of the flow area. This further induces a very strong unstable effect on the Type-II instability region as shown in Fig. 9.

V. CONCLUSIONS

This research extends the simple nonlinear model developed by Lin and Pan [7] to provide a qualitative nonlinear analysis in investigating the effects of different heater-to-riser configuration on the system stability. Four types of formation shape: (a) suddenly expansion; (b) suddenly contraction; (c) gradually expansion (diffuser) and (d) gradually contraction (nozzle), are considered in the present study. The conclusions in this paper can be summarized as following:

(1) The suddenly contraction structure provides a rather poor stability performance, which has a small stable region and only exists in the low power range. Respectively, the suddenly expansion structure exhibits a more excellent stability capability. The enlargement of diameter size has a stable effect both on the Type-I and Type-II instability regions.
(2) Considering the diffuser structure, the results reveal that the included angle has a negligible effect on the Type-I unstable region. On the other hand, in the high power region the effect of included angle may depend on how the form loss coefficient changes with the included angle. In the small included angle range ($\theta<60^o$), an increase in the included angle leads to the increase of two-phase form loss. This may destabilize the system in the Type-II instability region. However, in the medium-to-large included angle range ($\theta>60^o$), the form loss coefficient changes slightly to induce a small effect on the system stability in the Type-II instability region.
(3) The results suggest that the increase of the area ratio in the diffuser system has a stable influence on the Type-I instability region. On the other hand, in the high power region the two-phase frictional loss can be reduced by enlarging the area ratio and further stabilize the Type-II instability region.
(4) The results indicate that the included angle seems to have a little effect both on the Type-I and Type-II unstable regions in the nozzle system. The contraction of flow area may have a stable effect on the Type-I instability in the low power region; however, strongly destabilize the Type-II instability in the high power region.

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NOMENCLATURE

A	cross sectional area $\left(m^2\right)$
A^+	non-dimensional cross sectional area, $=A/A_H$
D	equivalent diameter $\left(m\right)$
Fr	Froude number, $=u_s^2/gL_H$
$f_{1\phi}$	single-phase friction factor
$f_{2\phi}$	two-phase friction factor
g	gravitational acceleration $\left(ms^{-2}\right)$
h	enthalpy $\left(Jkg^{-1}\right)$
h_{fg}	latent heat of evaporation $\left(Jkg^{-1}\right)$
h^+	non-dimensional liquid enthalpy, $=\left(h-h_f\right)/h_s$
k	loss coefficient
L	length
L^+	non-dimensional length, $=L/L_H$
M	mass $\left(kg\right)$
M^+	non-dimensional mass, $=M/\rho_f A_H L_H$
N_s	number of nodes in the single-phase region of the heater
$N_{\exp}$	thermal expansion number, $=\beta h_{fg}\upsilon_f/C_{pf}\upsilon_{fg}$
N_{pch}	phase change number, $=Q/\rho_f A_H u_s \times \upsilon_{fg}/\upsilon_f h_{fg}$
N_R	number of nodes in the riser
N_{sub}	subcooling number, $=(h_f-h_i)/h_{fg}\times\upsilon_{fg}/\upsilon_f$
P	system pressure $\left(bar\right)$
Q	heating power $\left(W\right)$
q''	heat flux $\left(Wm^{-2}\right)$
q''^+	non-dimensional heat flux, $=q''/q''_0$
Re	Reynolds number, $=uD/v$
t	time $\left(s\right)$
t^+	non-dimensional time, $=t/t_{ref}$

u velocity $\left(m s^{-1}\right)$
u^{+} non-dimensional velocity, $=u / u_{s}$
ν kinetic viscosity
υ specific volume $\left(m^{3} kg^{-1}\right)$
υ_{fg} difference in specific volume of saturated liquid and vapor $\left(m^{3} kg^{-1}\right)$
z axial coordinate (m)
z^{+} non-dimensional axial coordinate, $=Z / L_{H}$

Greek symbols

β liquid thermal expansion coefficient $\left(K^{-1}\right)$
ΔP pressure drop (Pa)
ΔP^{+} non-dimensional pressure drop, $=\Delta P / \rho_{f} g L_{H}$
ρ density $\left(kg m^{-3}\right)$
ρ^{+} non-dimensional density, $=\rho / \rho_{f}$
$\Lambda_{1\phi}$ single-phase friction number, $=f_{1\phi} L_{H} / 2 D_{H}$
$\Lambda_{2\phi}$ two-phase friction number, $=f_{2\phi} L_{H} / 2 D_{H}$
λ length of the boiling boundary (m)
λ^{+} non-dimensional boiling boundary, $=\lambda / L_{H}$

Subscripts

ch heated channel
e exit of heated section
f frictional pressure drop or saturated liquid
g gravitational pressure drop or saturated vapor
H heater
i inlet of the heated section
R riser
Re exit of the riser
1ϕ single-phase
2ϕ two-phase
0 steady state

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