RESEARCH ON THE EFFECTS OF LOCAL THROTTLING ON THERMAL-INDUCED TWO-PHASE FLOW INSTABILITIES IN THE TYPICAL COOLANT OPEN-CHANNEL SYSTEM IN THE NUCLEAR REACTOR CORE

by

***Jianping LONG*[a], *Bao-Wen YANG*[b], *Bin ZHANG*[a*], and *Sipeng WANG*[c]**

[a] School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China
[b] DEQD Institute for Advanced Research in Multiphase Flow and Energy Transfer, Delta Energy Innovation Technology, Qingdao, China
[c] College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, China

Original scientific paper
https://doi.org/10.2298/TSCI2205095L

Thermal-induced two-phase flow instabilities could badly slow the runtime performance of two-phase systems, such as boiling water reactor core, and even endanger the safe operation. Hence, many researchers have carried out numerous researches on flow instability characteristics, but few publications cover the effects of local throttling on two-phase flow instabilities in open-channel systems such as coolant rod bundle subchannel with spacer grids in the nuclear reactor core. This paper provides a numerical study on the effects of local throttling on two-phase flow instabilities in a simplified typical coolant open-channel system in a nuclear reactor core by using the NUSOL-SYS code. The effects of local throttling ratio, throttling position, and other throttling parameters on the stability of the boiling channel system were carried out. The results show that usually in uniformly distributed throttling conditions, the stability of the system and high throttling ratio are positively correlated. In fixed throttle ratio conditions, the stability of the system is positively correlated with the distance from the throttling region to the entrance and local void fraction. If throttling regions are uniformly arranged along the heating channel with a certain value, the number of throttle regions will enhance the instability of the system. Besides, this paper preliminarily proposed a criterion function f(n, RT, α) to study the complicated throttling effects on flow instability which could provide technical reference for the safe design and operation of two-phase systems, especially, the reactor core.

Key words: *two-phase flow, throttling, instabilities, open-channel system, stability map*

Introduction

Two-phase flow stability in a boiling channel is an extremely important concern in all two-phase flow industrial equipment such as nuclear reactor cores, steam generators, and so on for safety in operation. However, in a two-phase flow system, due to the feedback delay and the existence of minor disturbances, there would be a two-phase flow instability phenomenon, which could bring hidden trouble to the safe operation of the two-phase flow system,

* Corresponding author, e-mail: binzhang@mail.xjtu.edu.cn

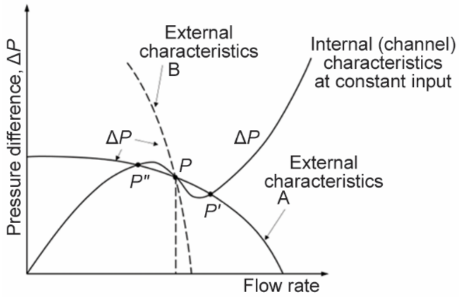

Figure 1. Pressure-drop-flow-rate characteristic curve in a two-phase flow system [2]

and may lead to earlier critical heat flux (CHF), equipment failure and other safety problems. In view of this topic, many researchers around the world have carried out plenty of research.

Two-phase flow instability in a boiling channel was first analyzed successfully in Ledinegg [1]. He studied this in detail and confirmed that it is one of the two-phase flow instability phenomena named flow drift, later called Ledinegg flow instability. The main characteristic Ledinegg flow instability is that when the operating condition is in the negative slope region of the channel demand pressure-drop-flow-rate curve (the internal characteristic of the channel in fig. 1), a small disturbance leads to the system migration from one stable condition to another stable condition. The precise criterion for the Ledinegg flow instability can be described by the following formula:

$$\frac{\partial \Delta P}{\partial G_{\text{int}}} \leq \frac{\partial \Delta P}{\partial G_{\text{ext}}} \tag{1}$$

In addition to flow drift, there are density wave flow instability, pressure drop flow instability, and so on. A systematic review of flow instability studies has been carried out for the first time by Boure *et al.* [3] based on the previous flow instability research, in which the mechanism and characteristics of various flow instability phenomena were described and the previous researches were summarized. It is proposed that flow instability can be divided into static instability and dynamic instability. The static instability refers to the pressure drop-flow multi-value correspondence of the hydrodynamic characteristic curve and the aperiodic flow drift of the system. While dynamic instability refers to the self-sustaining or divergent periodic oscillations of the thermal-hydraulic parameter in the two-phase flow system.

Later in Kakac *et al.* [2] and Ruspini *et al.* [4] updated reviews on the studies of flow instabilities based on Boure *et al.* [3], and further extended and complemented recent studies on flow instability. Through their research, we can see that the current studies on flow instability mostly focus on single channels, and parallel multi-channel with rectangular and circular shapes in experimental, theoretical, and numerical. Few researchers have studied the flow instability in open channels that are reviewed below.

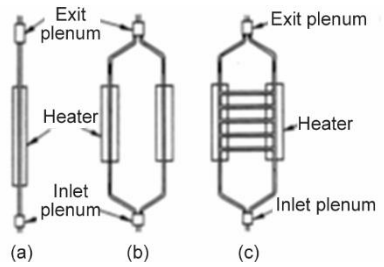

Figure 2. Test section of single, two parallel, and cross-connected parallel channels [5]

Veziroglu *et al.* [5] carried out a parallel two-channel flow instability study by using Freon as the working fluid and compared the cross-connected parallel channel system with single and parallel channel systems, as shown in fig. 2. The results show that the flow instability of parallel channels with transversely connected tubes is slightly different from that of conventional channels within their experimental conditions. The main reason for this slight instead of obvious difference is that these channel systems were heated symmetrically, thus little cross flow through transversely connected tubes emerged between the parallel channels, which was supposed to significantly affect the stability of the system. Similar studies were carried out by Kakac *et al.* [6, 7] with several channels in a parallel channel system extended from two to four, fig. 3. There had been the same limitations in their experiments since no asymmetric heating was adopted. Therefore, they reached the same conclusion that the cross-connected tubes have little impact on the two-phase flow instability in the parallel channel system.

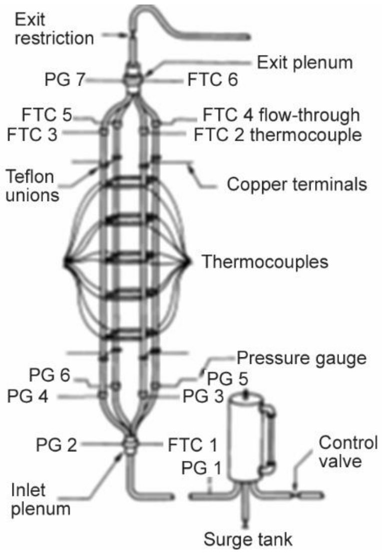

Figure 3. Test section of four channels with cross connections [7]

Whitfield and Roy [8] carried out an experimental study on the flow instability in 16-rod bundle channels with freon as the working fluid in 1995. Their results showed that there are both periodic and disordered flow fluctuations in the rod bundle channels. The authors believe that the flow instability in the rod bundle channels is difficult to evaluate and predict effectively due to the limitation of experimental resolution and systematic error.

Goutam and Jagdeep [9] studied the whole core instability in 2008 based on the development of an improved system code, considering neutron transport and fuel heat conduction. The results showed that the neutron feedback could weaken the stability of the system.

Shi *et al.* [10] built an experimental loop similar to study the flow instability. In the process of the study, they monitored two kinds of flow instability phenomena (flash instability and density wave instability). The flash instability appeared after the establishment of the single-phase natural cycle, while the density wave instability appeared after the establishment of the two-phase natural cycle. The density wave instability is abated by the increase of loop system pressure and finally disappears. Their study also showed that the change of heating rate in a certain range had no obvious effect on flow instability.

Lu *et al.*[11] used the fast Fourier transform method to simulate and analyze the flow instability of the reactor core channels based on the ocean-based flow instability analysis code. In order to obtain the characteristics of flow instability containing neutron-thermal coupling in static and rolling conditions. The results show that under static conditions, the channel with the largest heating power preferentially produces the flow instability of neutron-thermal coupling, and its fluctuation frequency corresponds to its natural frequency, while under rolling conditions, all parallel channels are affected by rolling motion and neutron-thermal coupling effects, but only the natural frequency of the highest power channel dominates, and the flow instability occurs firstly.

Cheng *et al.* [12] carried out an experimental study on the flow instability of 3×3 rod bundle channels in the natural circulation system. The main research contents include the influence of inlet subcooling, heating power, and the location of the regulator in the natural circulation system on flow instability.

Wang *et al.* [13, 14] studied the effects of radial asymmetric heating and axial inhomogeneous heating on the flow instability of 3×3 rod bundle channels based on the 1-D system code. The effects of different radial heating power ratios, power peak value, power peak position, power curve shape on the stability boundary of the system were discussed and analyzed.

Even so, most of the current studies rarely consider the existence of throttling in the channel, most of the research are done by considering the resistance coefficient at the entrance and exit of the channel. In view of that, there are many installations which are consisting of parallel open channels with local throttling regions such as coolant subchannels in the nuclear reactor core with spacer grids and rod bundle channels in the steam generator with solder joints in some nuclear power systems or other similar geometric characteristics. Therefore, it is of great significance to study the flow instability in open-channel systems for the safe operation of such nuclear power systems. Thus, a preliminary study of the effect of the resistance elements, *i.e.* throttling, on the flow instability in the simplified 2×1 coolant open-channel system in the nuclear reactor core is present in this paper. The effect of the throttle position, the throttle value, and the number of throttling arrangements on the flow instability in the open channel system are carefully investigated.

Flow instabilities in open-channel

Validation of the numerical model

The NUSOL-SYS code [15] was adopted in this study. According to Ambrosini and Ferreri [16], flow instabilities could be effectively simulated by using the non-homogeneous, non-equilibrium model and the semi-implicit numerical scheme. Thus, the non-homogeneous, non-equilibrium model and the semi-implicit numerical scheme are chosen for our study. Solberg *et al.* [17] had provided an experimental study on the flow instability in a boiling channel. In their study, the test section was a heated circular pipe, and by paralleling a large bypass channel at both ends of the inlet and outlet of the heating pipe to maintain the stability of the inlet and outlet pressure of the test section, the pressure boundary condition is obtained. After that, their experimental data was used to benchmark the numerical simulation scheme for the two-phase flow instability numerical studies by many researchers. To validate the feasibility and reliability of the method used in our study, Sorberg's experimental data [17] was used in this paper. Table 1 shows the settings in Sorberg's experiment, and the corresponding computational geometric model, as well as the nodalization, is shown in fig. 4.

Table 1. Experimental conditions and parameter settings in Solberg's experiment [17]

	Parameters	Values
Heating channel	Geometry	Circular
	Internal diameter [m]	0.00525
	Heating length [m]	2.9
	Roughness [m]	2.5e-5
Operating conditions	Inlet Reynolds number	4.78e-4
	System (outlet) pressure [atm]	80
	Inlet temperature [°C]	139.6-291.8
	Inlet pressure loss coefficient	17.8
	Exit pressure loss coefficient	0.03

The main parts are a large bypass pipe and a heating pipe whose inlet and outlet are connected by branch parts. The inlet pressure and temperature are set by a time-dependent control volume and a connected single junction. The outlet pressure is controlled by another time-dependent control volume and a single junction connected to it. The mass flow rate in the test section is determined by inlet and outlet pressure, and channel characteristics. In the calculation, the heating channel is divided into 50 control volumes. The heating power condition is used to simulate the heating condition in the experiment. The thermal component is very thin with high thermal conductivity and low thermal capacity to reduce the calculation error caused by the heat storage in the solid material of the heating pipe. The diameter of the bypass pipe is set to 10 times the heating pipe to ensure the realization of the constant pressure boundary conditions.

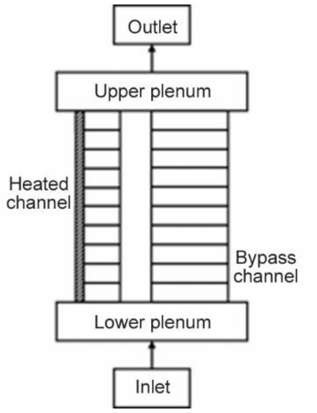

Figure 4. Nodalization of the computational geometric model for benchmark

Figure 5 shows the stability map comparison between the calculational results and the experimental data based on phase change number and subcooling number (Zuber number and Ishii number proposed by Zuber and Ishii to estimate the stable boundary for two-phase flow system in 1979 [18], which is widely used in the study of two-phase flow instability). The definitions of these two dimensionless numbers are shown as the function:

– Phase change number
$$N_{\mathrm{pch}} = \frac{Q}{Gh_{\mathrm{fg}}}\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}} \tag{2}$$

– Subcooling number
$$N_{\mathrm{sub}} = \frac{\Delta h}{h_{\mathrm{fg}}}\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}} = \frac{h_{\mathrm{f}} - h_{\mathrm{in}}}{h_{\mathrm{fg}}}\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}} \tag{3}$$

where ρ [kgm^{-3}] is the density, h [kJkg^{-3}] – the enthalpy, Q [kW] – the power, G [kgs^{-3}] – the flow rate, and the subscripts f, g, and in – the liquid phase, vapor phase, and inlet, respectively.

We can see from fig. 5 that the simulation results feed well with the experimental data (the maximum error is no more than 10%), which means our numerical simulation scheme can be applied to study the two-phase flow instability phenomena.

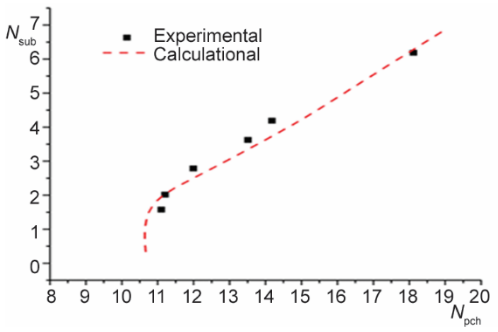

Figure 5. Computational stability map compared with experimental data

Typical open-channel

In order to study the effect of throttling on the flow instability in the open-channel system, the flow instability phenomena in the open-channel system with and without throttling regions are studied in this paper. In this section, we introduce the typical computational model for the simplified open-channel system, including the control body partitions, initial conditions, boundary conditions, throttling regions, and other simulation settings, as well as the flow oscillation characteristics and the stability boundary map of the typical open-channel system.

The object of this paper is a 2×1 open-channel system. Figure 6 shows the nodalizations for the typical open-channel system used in numerical model and set-up.

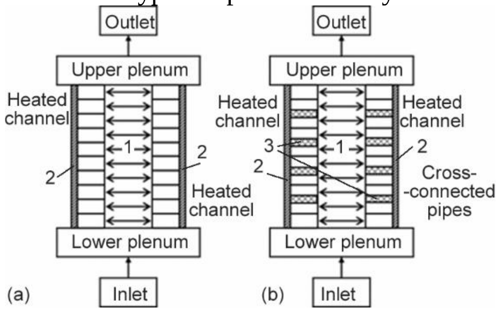

Figure 6. Diagram of geometry nodalizations for the simplified typical (a) and throttled typical and (b) open-channel systems in the nuclear reactor core; *1 – cross-connected pipe, 2 – heat structure and 3 – throttling region*

The sensitivity analysis for time steps and nodalizations would not be discussed here since they had been described in detail in the previous research [19]. In this study, finally, the node number is 50, in other words, a single channel is divided into 50 control volumes, the maximum time step is set as 0.01 seconds, the minimum time step is set as 10^{-10} seconds. In the actual reactor core, the pressure difference between the two adjusted channels is pretty small since there are so many subchannels. Thus, in our simulation, the inlet pressures for the two channels are set as the same. Table 2 shows the detailed conditions in our simulation.

Table 2. The simulation conditions in this study [20-22]

Shape of channel	Circular
Diameter of heated channel 1	0.0124 m
Diameter of heated channel 2	0.0124 m
Length of heated channels	3.6576 m
Surface roughness	2.5e-5 m
Inlet pressure	7 MPa
Inlet subcooling number	0.25-8
Inlet flow energy loss coefficient	23
Outlet flow energy loss coefficient	5
Outlet pressure	6.89 MPa
Working fluid	Water
Throttling ratio	0-0.9

To obtain the flow instability phenomena in simulation, a similar method has been used as that used in experiments. Increasing the heat flux step by step rapidly, within 0.1 seconds, with a fixed value such as 1 kW and then keep for a period of time for example 50 seconds until the mass-flow rate goes into self-sustaining (amplitude is large than 10%) and even diverge oscillation, figs. 7 and 8, just sketch, specific depending on conditions. In this way, the flow instability phenomena happen. The flow rate and heating power at this moment are known as critical mass flow rate and power.

Throttling in open-channel

There are throttles such as local blockage and spacer grid widespread existed in the open-channel system (rod bundle channels), which will affect the flow and heat transfer in the channel and thus affect the stability of the system. In practice, the influences of the existence of these throttles on the flow are mainly composed of two parts: on the one hand, it would reduce the local flow area of the channel, which leads to the increase of resistance and the increase of local pressure drop; on the other hand, it may lead to forced cross-flow between the adjacent channels, like the mixing effect caused by mixing vane. In order to simplify the effects of the throttling region on flow instability in the research, this paper will ignore the throttle-induced cross flow, and only the throttling effects are studied. In order to quantitatively study the effect of throttling, a throttling ratio, *RT*, is defined:

$$RT = \frac{A_{\text{fn}} - A_{\text{tn}}}{A_{\text{fn}}} \tag{4}$$

where RT is the throttling ratio, A_{fn} and A_{tn} – the flow area of the normal region and throttling region, respectively. The larger the throttling ratio is, the larger the throttled area is, thus resulting in a smaller flow area.

As fig. 6 shows, the nodalizations for the throttled open-channel system are similar to the typical open-channel system, 50 control volumes are divided in the axial direction (flow direction). Throttling was realized by changing the diameters and flow area of the throttled control volumes, and the other settings are consistent with the typical channel system.

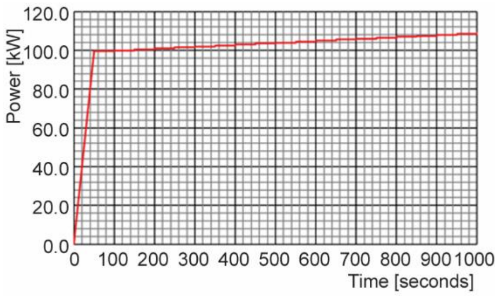

Figure 7. Diagram of the heating power varies time

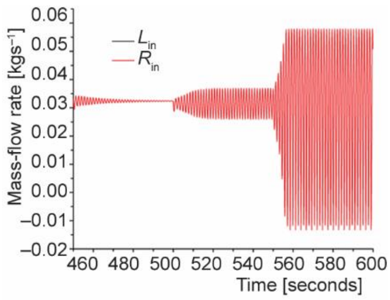

Figure 8. Diagram of the inlet mass-flow rate oscillations in the heating channels

Results and discussions

In our study, the main research contents are the effects of the throttling ratio value, location, and number on the stability of the 2×1 subchannel system. The simulation results would be analyzed.

Throttling ratio effects

When studying the throttling ratio effects, five throttles are uniformly arranged in the whole heating channels with the changeable RT, as shown in fig. 9. The range of RT is 0-0.9. When the RT is 0, it represents the normal open-channel system without any throttling. In order to evaluate the influence of the throttling ratio on the overall stability of the system, the stability boundary maps in terms of subcooling number and phase change number under different throttling ratios are obtained by calculating the cases with different inlet subcooling conditions.

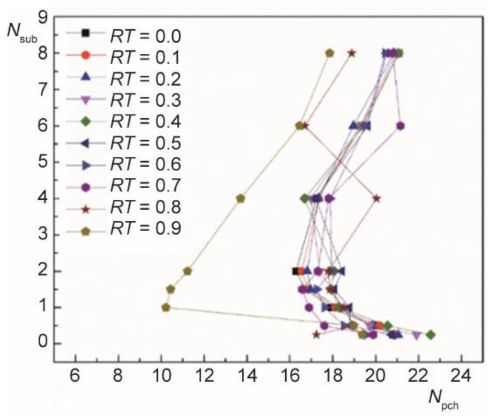

Figure 9. Stability boundary of 2×1 open-channel system with different *RT*

From fig. 9 it can be seen that when the throttling region are uniformly distributed in the channel, the small RT has little effect on the stability of the system, but when the RT is large, the stability of the system is affected obviously, especially when the throttle ratio is larger than 0.6 with relatively complex impacts. The authors analyze that the influence is also related to the throttle location (*i.e.* local thermal-hydraulic conditions). Therefore, the influence of the throttling position is studied in the next part.

Throttling location effects

Based on the previous analysis on the influence of the throttling ratio on the flow instability, it can be seen that when the throttling ratio is large (greater than 0.6), throttling has a significant impact on the system stability. Therefore, in order to highlight the difference between the impacts of the location of the throttling section on flow instability, the larger throttling ratios of 0.7-0.9 (such as severe blockage in rod bundle subchannels) are used for comparative analysis. The specific method is to divide the whole channel into four parts from the inlet to the outlet with the throttling arranged at the 4 positions respectively, as shown in fig. 6.

In order to evaluate the influence of throttling location on the overall stability of the system, the stability boundary maps in terms of subcooling number and phase change number are obtained by calculating the cases with different inlet subcooling.

From fig. 10 we can see that when the throttling is close to the inlet, the stable boundary of the system will shift to the right (unstable region), which means it enhances the stability of the system as the throttling region is far away from the inlet, the existence

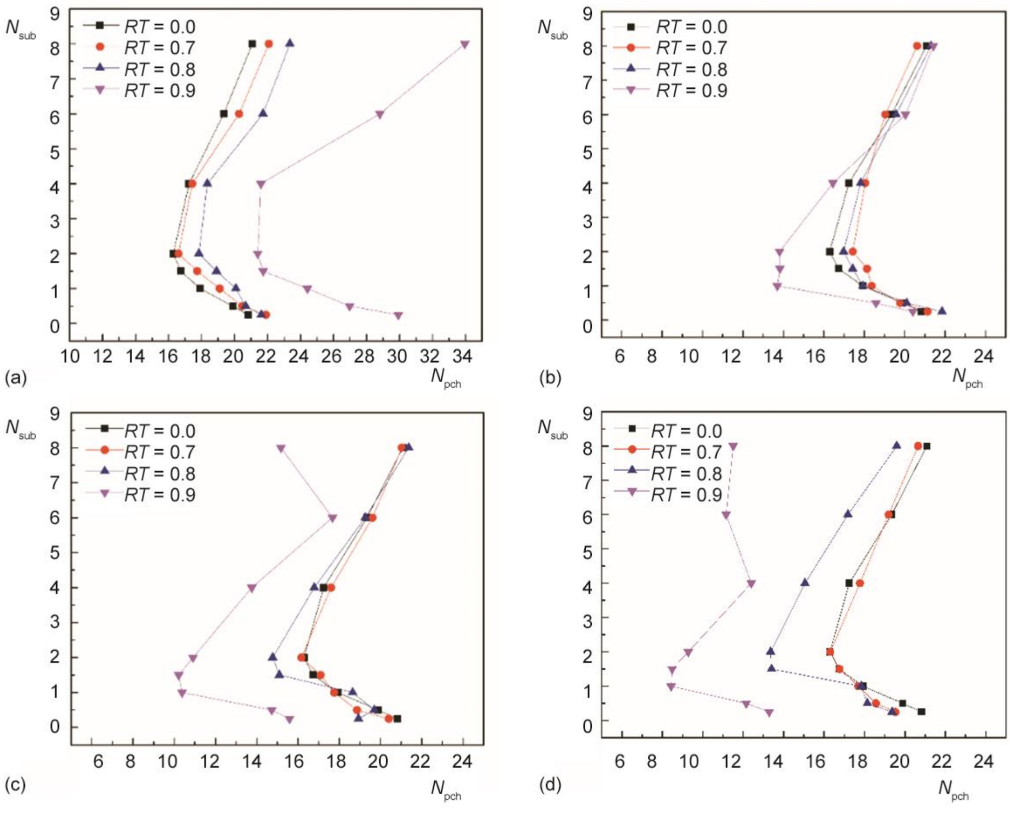

Figure 10. Stability boundary of 2×1 open-channel system with throttling arranged at different axial locations; (a) Z = 0.2, (b) Z = 0.4, (c) Z = 0.6, and (d) Z = 0.8. Z means the dimensionless axial length, for Z = 0 is the inlet and Z = 1 is the outlet

of throttling will make the stable boundary of the system shift to the left (stable area), that is to say, the stability of the system will be weakened. Moreover, the larger the throttle is, the faster the transition condition (enhance to weaken) occurs. It should be noted that this phenomenon is more likely to occur under low subcooling conditions. This is because the void fraction in the channel increases gradually from the inlet to the outlet along the flow direction, and the void fraction corresponding to the low subcooling conditions reaches the critical value for flow instability earlier. The farther the throttling is from the inlet, the smaller the impact on the single-phase pressure drop is, and on the contrary, the greater the influence on the two-phase pressure drop is thus the stability is weakened.

Number of throttling sections effects

The effects of the number of throttling sections distributed uniformly with the same *RT* on flow instability in the 2×1 open-channel system can be studied out through the stable boundary comparison of two extreme conditions-completely throttled and non-throttled, in other words, two heating 2×1 open-channels system with different diameters. Figure 11 shows the results of these two cases with 12.4 mm and 5.55 mm (*RT* = 0.8) in heating channel diameters. The figure shows that the open-channel system with a heating diameter of 5.55 mm is more stable than the one with 12.4 mm on the constant pressure inlet and outlet boundary conditions. This is mainly due to the lower mass flow rate in the smaller channel system with the constant pressure boundary thus inducing a smaller pressure difference between single-phase and two-phase which could reduce the driving force of flow instability. Finally, the stability of the system is enhanced.

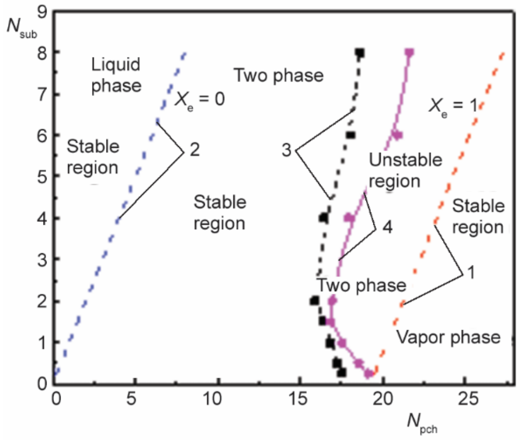

Figure 11. Stability boundary of 2×1 open-channel system with 12.4 mm and 5.55 mm (*RT* = 0.8) heating channel diameter; *1 – Xe = 1, 2 – Xe = 0, 3 – Stability boundary (D = 12.4 mm, RT = 0.8), 4 – Stability boundary (D = 5.55 mm, RT = 0.8)*

For non-uniformly distributed throttling sections with different *RT*, the effects on the flow instability in a 2×1 open-channel system could be described by a simplified function $f(n, RT, \alpha)$. The definition of this function is:

$$f\left(n,RT,\alpha\right)=f\sum_{i=1}^{x}(RT)_i-k\sum_{j=1}^{n-x}(RT)_j\alpha_j\begin{cases}>0, & \text{Enhance the system stability}\\=0, & \text{Little impact on the system stability}\\<0, & \text{Weaken the system stability}\end{cases} \tag{5}$$

$$\left\{0\le n\le N;\quad 0\le RT<1;\quad 0\le\alpha\le1\right\};\quad \Delta P=C$$

where f and k are enhanced and weaken the weighting coefficient of throttling on system stability respectively, n – the total number of throttling regions in the system, N – the total control volume number of the channel, ΔP – the constant pressure inlet and outlet boundary, C – the certain pressure drop for the pressure boundary, x – the number of throttling region on liquid phase region, and α – the local vapor volume fraction in the j throttling region area. The concrete values of f and k can be obtained by fitting enough reliable data to get the corresponding empirical formulae of $f(n, RT, \alpha)$ and it could be further revised to a semi-empirical equation based on physical mechanisms calculating a large number of flow instability cases. This paper only makes a preliminary discussion on the stability criterion for the effects of throttling on the flow boiling system. Further study on this criterion is ongoing and would be carried out in the future based on experimental data and physical mechanisms so that it can be used in engineering situations.

Conclusions

In this paper, the two-phase flow instability in rod bundle subchannels is studied by simplifying the subchannel into parallel channels with upper and lower plenum with an open-channel flow instability calculation model established by using the NUSOL-SYS code [15] to study the effect of throttling on the flow instability in this kind of simplified open-channel system. Through the calculation and analysis of different throttling ratios, throttle locations, and the number of throttle regions, the following conclusions can be drawn within the scope of this study.

- The existence of the throttling region would affect the instability of the system. At low throttling, the effect is slight. When the throttling is greater than a certain value, the uniformly arranged throttling usually increases the stability of the system, and the greater the throttling, the greater the influence.
- When the throttle ratio is fixed, the stability of the system will also be changed when the throttle region is close to the inlet, which would enhance the stability of the system, and weaken the stability of the system when the throttle region is close to the outlet. When the throttle region is in the middle of the channel, the influence of the throttle region on the system stability is related to the local void volume fraction. The specific influence law needs further study.
- When the throttle ratio is certain and the throttle region is uniformly arranged in the heating channel, the number of throttle regions will also affect the stability of the system. With the increase of the number of throttle regions, the stability of the system will be weakened especially in large throttling conditions.
- The impacts of the throttle on the stability of the open-channel system are very complicated. This paper only provides a pretty worthy idea on the study of throttling effects on flow instability especially the criterion function $f(n, RT, \alpha)$ which of course, requires a more in-depth study based on enough reliable data and physical mechanisms.
- The research in this paper provides a simplified exploration of the reactor core subchannel flow boiling instability conditions, which gives a reference for the in-depth and further study on the two-phase boiling flow instability phenomenon in the core subchannel. In addition, this study explores the influence of the two special geometric characteristics of reactor core subchannel opening and throttling on the flow boiling instability. It could provide an effective engineering reference to enhance the stability of the boiling channel system, reduce or eliminate the hidden danger of flow instability in boiling two-phase flow system, which usually leads to flow-induced vibration, thermal fatigue, early CHF, and thus endangers the safe operations of boiling channel system.

References

[1] Ledinegg, M., Instability of Flow during Natural and Forced Circulation, *Die Waerme, 61* (1938), 8, pp. 891-898

[2] Kakac, S., Bon, B., A Review of Two-Phase Flow Dynamic Instabilities in Tube Boiling Systems, *International Journal of Heat and Mass Transfer*, *51* (2008), 3-4, pp. 399-433
[3] Boure, J. A., *et al.*, Review of Two-Phase Flow Instability, *Nuclear Engineering and Design*, *25* (1973), 2, pp. 165-192
[4] Ruspini, L. C., *et al.*, Two-Phase Flow Instabilities: A Review, *International Journal of Heat and Mass Transfer*, *71* (2014), Apr., pp. 521-548
[5] Veziroglu, T. N., Lee, S. S., Boiling Flow Instabilities in a Two Parallel Channel Upflow System, Final report, Miami Univ., Coral Gables, Fla., USA, 1969
[6] Kakac, S., *et al.*, Transient Boiling Flow Instabilities in a Multi-Channel Upflow-System, *Warme Und Stoffubertragung*, *10* (1977), 3, pp. 175-188
[7] Kakac, S., *et al.*, Sustained and Transient Boiling Flow Instabilities in a Cross-Connected Four-Parallel-Channel Upflow System, *Revista Costarricense De Ciencias Medicas*, *23* (1974), 1-2, pp. 33-43
[8] Whitfield, K., Roy, R. P., Boiling Flow through a Rod-Bundle Channel: Steady States and Dynamic Instabilities, *International Journal of Heat and Mass Transfer*, *38* (1995), 8, pp. 1409-1425
[9] Dutta, G., Doshi, J. B., A Characteristics-Based Implicit Finite-Difference Scheme for the Analysis of Instability in Water Cooled Reactors, *Nuclear Engineering & Technology*, *40* (2008), 6, pp. 477-488.
[10] Shi, S., *et al.*, Experimental Investigation of Natural Circulation Instability in a BWR-Type Small Modular Reactor, *Progress in Nuclear Energy*, *85* (2015), Nov., pp. 96-107
[11] Lu, X., *et al.*, Theoretical Investigations on Two-Phase Flow Instability in Parallel Channels under Axial Non-Uniform Heating, *Annals of Nuclear Energy*, *63* (2014), Jan., pp. 75-82
[12] Cheng, K., *et al.*, Experimental Investigation on Flow Characteristics of Pressure Drop Oscillations in a Closed Natural Circulation Loop, *International Journal of Heat and Mass Transfer*, *122* (2018), July, pp. 1162-1171
[13] Wang, S., *et al.*, RELAP5 Investigation on Subchannel Flow Instability, *Kerntechnik*, *81* (2016), 3, pp. 337-345
[14] Wang, S., *et al.*, The Influence of Non-Uniform Heating on Two-Phase Flow Instability in Subchannel, *Nuclear Engineering and Design*, *345* (2019), 345, pp. 7-14
[15] Shan, J., Development of Multi-Scale High-Fidelity System Analysis Code NUSOL-SYS, CDNET-2018, Chengdu, China, 2018
[16] Ambrosini, W., Ferreri, J. C., Analysis of Basic Phenomena in Boiling Channel Instabilities with Different Flow Models and Numerical Schemes, *Proceedings,* 14th International Conference on Nuclear Engineering, Miami, Fla., USA, 2006, pp. 889-900
[17] Solberg, K. O., *Resulats des Essais d' Instabilities sur la Boucle' Culine' et Comparisons avec Code de Calcul*, Centre d'Etudes Nuclear, Grenoble, France, 1966
[18] Ishii, M., Study on flow instabilities in two-phase mixtures, Report No. ANL-76-23, Argonne National Laboratory, Argonne, Ill., USA, 1976
[19] Long, J., *et al.*, Numerical Simulation Investigation on Two-Phase Flow Instabilities in Two-Parallel-Channel, Nureth-18, Portland, Ore., USA, 2019
[20] Wang, S., *et al.*, RELAP5 Investigation on Subchannel Flow Instability, *Kerntechnik*, *81* (2016), 3, pp. 337-345
[21] Colombo, M., *et al.*, RELAP5/MOD3.3 Study on Density Wave Instabilities in Single Channel and Two Parallel Channels, *Progress in Nuclear Energy*, *56* (2012), Apr., pp. 15-23
[22] Papini, D., *et al.*, Time-Domain Linear and Non-Linear Studies on Density Wave Oscillations, *Chemical Engineering Science*, *81* (2012), Oct., pp. 118-139

Paper submitted: December 6, 2021
Paper revised: July 15, 2022
Paper accepted: July 20, 2022