Nuclear Science and Techniques **20** (2009) 111–117

Two-phase flow instability in a parallel multichannel system

HOU Suxia

Department of Physics, the Second Artillery Engineering Institute, Xi'an 710025, China

Abstract The two-phase flow instabilities observed in through parallel multichannel can be classified into three types, of which only one is intrinsic to parallel multichannel systems. The intrinsic instabilities observed in parallel multichannel system have been studied experimentally. The stable boundary of the flow in such a parallel-channel system are sought, and the nature of inlet flow oscillation in the unstable region has been examined experimentally under various conditions of inlet velocity, heat flux, liquid temperature, cross section of channel and entrance throttling. The results show that parallel multichannel system possess a characteristic oscillation that is quite independent of the magnitude and duration of the initial disturbance, and the stable boundary is influenced by the characteristic frequency of the system as well as by the exit quality when this is low, and upon raising the exit quality and reducing the characteristic frequency, the system increases its instability, and entrance throttling effectively contributes to stabilization of the system.

Key words Flow instability, Parallel multichannel system, Stable boundary, Two phase flow, Flow oscillation

1 Introduction

Thermal and hydrodynamic instabilities of two-phase flow in a boiling channel have been studied in the part two decades[1–4]. Subsequently, the subject has been increasingly extended to parallel multichannel systems[5,6], in view of the importance to the safety of boiling water reactors, steam generators of fast breeder reactors and advanced thermal reactors.

The two-phase flow instabilities in a parallel-channel system can be classified into three types: (1) static instabilities, head flow oscillation of the Ledinegg type; (2) pressure-drop oscillation, flow oscillation in common phase in different channels; and (3) density-wave oscillation(DWO), flow oscillation in different phase and different channels, with constant total flow rate in the channels. At the design stage, considerations are taken to avoid Type 1 instability. Instability of Type 2 occurs under surface boiling in the preheater, or when an accumulator is installed between the test section and pump. This instability was characterized by the total flow rate oscillation in the test section in 0.4–2.0 seconds[7], and in common phase between the two channels. Flow reversal occasionally occurred. Without preheater surface boiling or accumulator installation, Type 2 instability cannot be generated in the apparatus.

Type 3 instability is caused by interactions between parallel multichannel systems. In boiling systems, DWO is due to multiple regenerative feedbacks existing between the flow rate, vapor generation rate and pressure drop. Inlet flow fluctuations create enthalpy perturbations in the preheated region, and consequently produce enthalpy perturbations in the boiling region, *i. e.*, waves in the vapor generation rate that follow the flow through the channel. These perturbations of vapor generation rate create perturbations of pressure in the superheated region as well as of pressure drop in the boiling region. These perturbations of pressure and pressure drop are immediately transmitted to the boiling boundary, through which the perturbations are fed back into the inlet flow. However, this type of instability is often confounded with Types 1 and 2 instabilities, hence insufficient scrutiny of Type 3 instability in many studies. Sufficient data available for verifying analytical models of flow instability are required to

* Corresponding author. *E-mail address:* hsx@stu.xjtu.edu.cn

Received date: 2008-09-04

establish a design tool for predicting the stability boundary. This is of practical use in parallel multichannel systems. In this work, an experimental study was performed on the two-phase instability observed in a parallel multichannel system, in an attempt to obtain data for verification of analytical methods to predict the stability boundary against Type 3 instability, and to have a better understanding of the phenomena and the mechanism involved. The results were compared with the theoretical calculations in Refs.[7,8].

2 Experiment

Fig.1 shows the schematic diagram of a parallel multichannel system for this study. The working medium is demineralized and deaerated water, which is circulated through the preheater and the test and the by-pass tube sections. The by-pass section imposes on the test section an external constraint of constant pressure drop between the inlet and exit, reproducing the boundary condition for density wave instability between the inlet and exit headers of parallel multichannel system with a large number of tubes. Flowing upwards through the test section, the subcooled water is heated into superheated steam, which enters the steam separator where the main and the by-pass streams recombine. In the condenser, the steam condenses and the water returns to the reservoir through the subcooler.

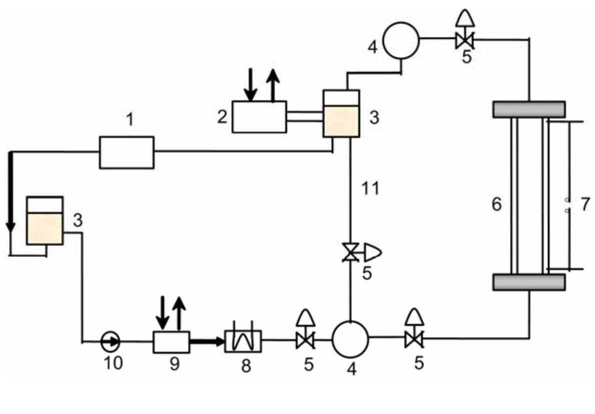

Fig.1 Schematic diagram of a parallel multichannel system. 1, subcooler; 2, condenser; 3, steam separator; 4, header, 5, flow control valve; 6, test section of two parallel tubes; 7, AC power; 8, preheater; 9, precooler; 10, pump; 11, by-pass.

The test section consists of two Incoloy-800 tubes of 5 m long, 10.0 mm inner diameter and 3 mm wall thickness. The tubes are heated by AC current passing the tube wall, and the heat flux is essentially uniform. The tube withstands high temperatures of up to about 800℃, which may occur under extreme steaming conditions in a once-through boiling water flow with uniform joule-heating.

Flow rates at the inlet and exit of the test tubes were measured by venture flow meters and strain gage transducers, with their response time to a stepwise change in flow being experimentally ascertained as <0.04 s. This response is adequate for measuring the flow oscillatory behavior of the density wave instability for a parallel multichannel system. The AC power to each test tube was measured with voltmeter and ammeter. The experimental conditions are listed in Table 1.

Table 1 Operation parameters of system

Parameters	Values
Tube Inner diameter, d_i / $\times10^{-3}$ m	10
Tube outer diameter, d_o / $\times10^{-3}$ m	13
Heated length, L / m	5.0
Inlet orifice loss coefficient, C_R	300–1100
Inlet subcooling, T_{sub} / ℃	50–250
Pressure, P / $\times10^5$ Pa	20–40
Mass flow rate, W / kg·m^{-2}·s^{-1}	100–420
Channel power, Q / $\times10^3$ W	40–70
Heat flux, q'' / $\times10^5$ kJ·m^{-2}·s^{-1}	1.8–5.6

3 Results

For measuring the Type 3 instabilities, the flow rate in both channels was kept constant. This was verified by measurements at the orifice with increased the flow rates obtained from the venture flow meter in the channels. Type 3 instabilities appeared with a phase difference of 180° between the two channels, with no occurrence of flow reversal, as shown in Fig.2. The oscillation amplitudes show a ratio of 0.1–95 between the same points, and at the inlet an increase of above ±100% of the mean flow rate can be observed. In stable regime, the difference of flow rate between the two channels was less than 0.3%, which is within experimental error, so that the flow distribution could be considered to be uniformly divided.

Being a multivariable and dynamic problem, the analysis of two-phase flow instability in parallel multichannel system with complex thermal-hydrodynamic boundary conditions can be carried out by use of multivariable frequency-domain theory which has developed up in the automatic control field. According to multivariable frequency-domain theory, the stable boundary analysis is discussed in Ref.[9]

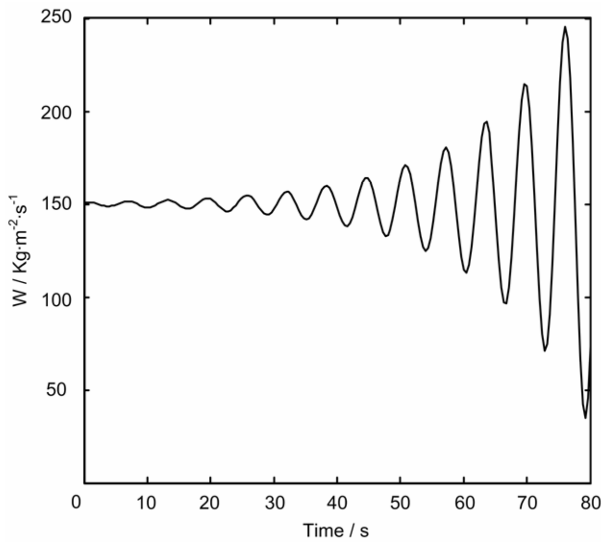

Fig.2 Typical trace of flow oscillation onset.

The results of an earlier experiment[6] showed that a power input difference of less than 2% between the two channels did not have a marked change in the flow instabilities. Hence, the two channels were provided with resistances paired to within 1%.

In an experiment for Type 3 instability study, the boundary between the stable and unstable regions is independent of the magnitude and duration of disturbance, and the nature of flow oscillation in the unstable region is independent of the initial disturbance, too, shortly after the disturbance. The flow instability test was conducted as follows. The water flow and pressure, and the input power, were adjusted to corresponding values in Table 1. The pressure and inlet subcooling were changed one by one in small steps to establish well-defined and self-sustained flow oscillations.

Fig.3 shows a typical trace of the inlet flow at the onset of instability by a slight increase of input power.

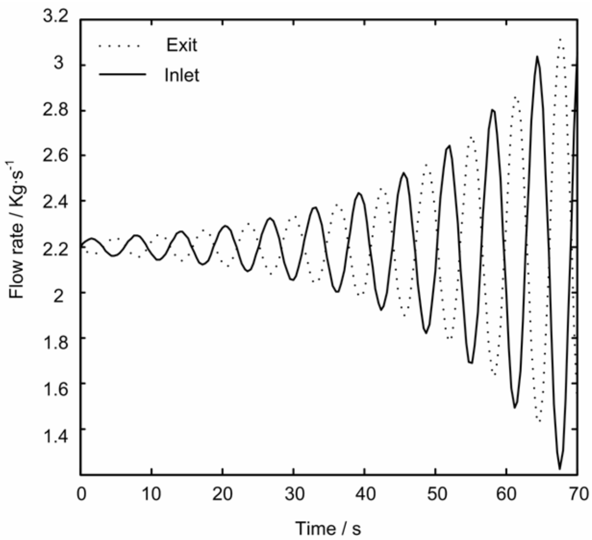

Fig. 3 Typical experimental results.

3.1 Stable boundary

The instabilities are examined by increasing the heat flux step by step, under constant flow rate and temperature at the inlet. If flow oscillation occurs in several minutes, the system is unstable. If not, artificial disturbance is added to the system until a flow oscillation occurs. And the system is deemed stable when the flow oscillation is seen to die upon removal of the disturbance. The stable boundary between the stable and unstable systems was determined in a large number of runs, in different the heat fluxes by varying the entrance throttling, average inlet velocity, inlet temperature, cross section and heater lengths. The standard conditions are summarized in Table 2.

Table 2 Reference conditions adopted for analysis

Parameters	Values
Average inlet velocity, $u_{\rm in}$ / m·s^{-1}	0.4
Heat flux, q''/ ×10^5 J·m^{-2}·s^{-1}	4.5
Inlet liquid temperature, $T_{\rm in}$ / ℃	95
Single-phase water region length, $L_{\rm B}$ / m	0.4
Throttling coefficient, $C_{\rm R}$ / kg·s^2·m^{-4}	320

The entrance throttling, *i.e.* the product of the resistance coefficient and density of the working medium, was changed by different orifices inserted between the inlet plenum and the flow meters. The results are shown in Fig.4. The pressure drop of the section L_B(single-phase water region) is proportional to the square of the inlet flow rate, the proportional constant would represent the coefficient of entrance throttle pressure drop. The system is found to become increasingly stable with rising resistance of the entrance orifice.

The effect of average inlet flow rate on stability is shown in Fig.5. It can be seen that, with rising average inlet velocity, the system stability increases, with a gradual rise in the average outlet quality (X_{out}) at the stable boundary.

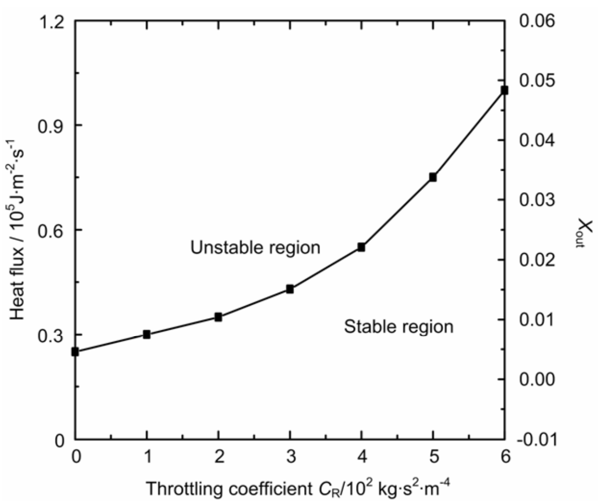

Fig.4 Stable boundary in reference to entrance throttling.

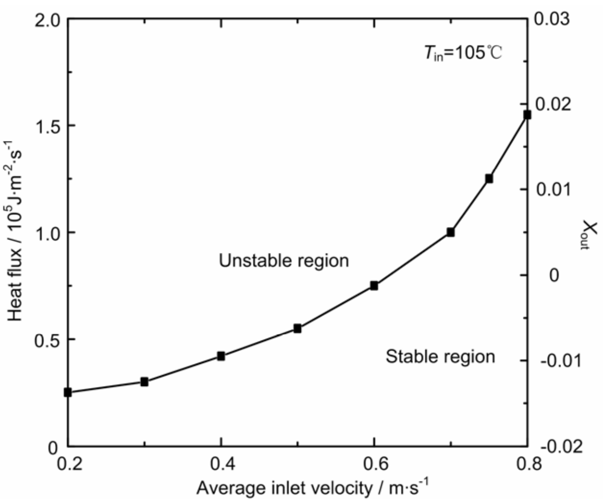

Fig.5 Stable boundary in reference to average inlet velocity.

Results of the experiment with different inlet temperatures (Fig.6) show little change of the average outlet quality along the stable boundary, even at 90–115℃ of the inlet temperature.

Fig.7 shows the experimental results with different heater lengths. The data were obtained with a heater in 3/4 the length of the standard heater, with the other parameter being the same as in Fig.5. Comparing the two figures, one finds that a short heater enhanced stability of the system. Shortening the heater to half standard length, we found stable flow irrespective of the heat flux at average inlet velocities of > 0.2 m/s.

The results in Figs.4–7 agree well with analytical results of the stable boundary in Ref.[6].

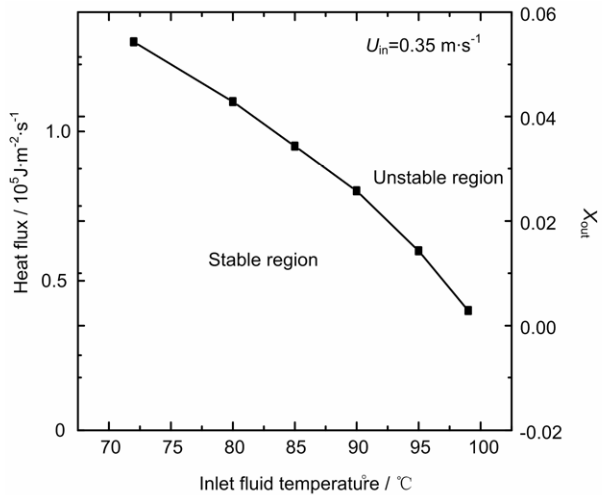

Fig.6 Stable boundary in reference to inlet liquid temperature.

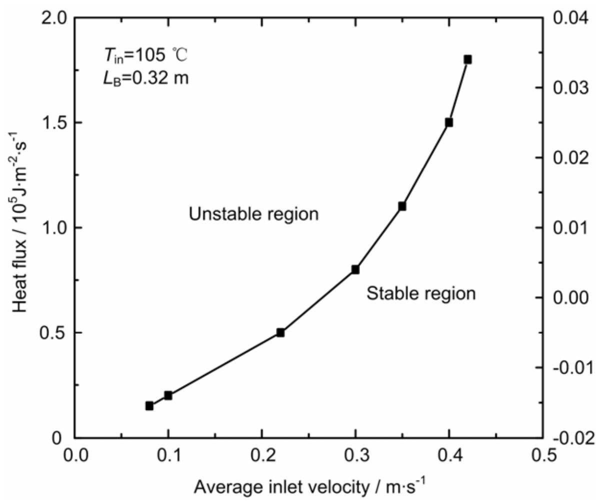

Fig.7 Stable boundary with shortened heater length.

3.2 Flow oscillation in unstable region

For a better insight into the flow oscillation, experiments were conducted in the unstable region indicated by the stability curve determined in Section 3.1. Fig.8 shows the heat flux at different average inlet velocities. It can be seen clearly that the amplitude ratio increases as the conditions change from the stable boundary to unstable region. For equal amplitude ratio, the curves in the unstable region look quite similar to that at the stable boundary. Similar results were obtained under other conditions.

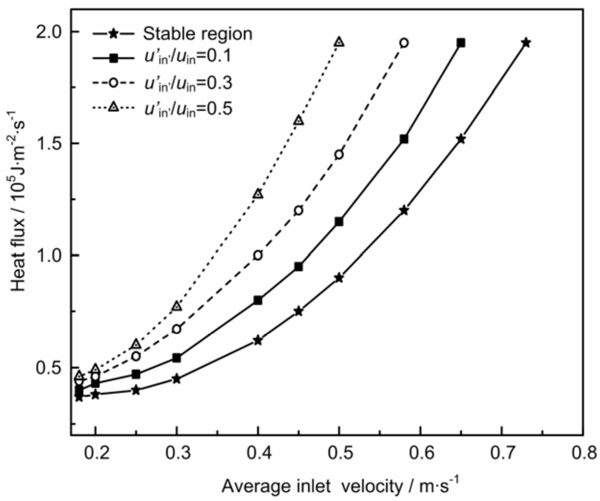

Fig.8 Variation of nature of flow oscillation with change in amplitude of flow oscillation.

As shown in Fig.9, the plots for oscillation period obtained under various conditions fall along a single line against the time for the fluid to pass through the preheating section. The plots show the results as follows.

(a) The oscillation period depends quite sensitively on the time for the fluid to pass through the preheating region.

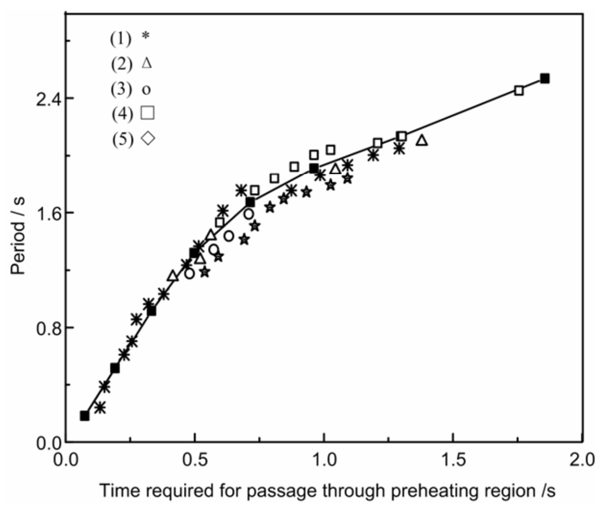

Fig.9 Period of flow oscillation in reference to time required for passage through preheating region. The plots were obtained under the following conditions. (1) u_{in}=0.25m/s in various heat flux, (2) u_{in}=0.25 m/s and q''= 3×10^5 J·m^{-2}·s^{-1} at various inlet liquid temperatures, (3) L_B=0.32 m and u_{in} =0.23 m/s in various heat fluxes, (4) u_{in} = 0.15 m/s in various heat fluxes, and (5) C_R=298.0 kg·s^2·m^{-4} and u_{in} = 0.25 m · s^{-1} in various heat fluxes.

(b) Actual length of the heater does not influence the period for L_B of 0.35–0.45m.

(c) The oscillation period decreased slightly with increasing entrance throttling, but increased with average inlet velocity. The plots can be fitted by $\tau_B = (h' - h_{in})\rho_i/q''$.

4 Discussion

The parameters that dominantly influence the instabilities in a parallel multichannel system can be analyzed based on phase analysis. A *characteristic frequency* can be named for a frequency at which a 180° phase shift is observed, hence a *characteristic gain* corresponding to it. The *characteristic gain* against heat flux is depicted in Fig.10a, and the horizontal line is the gain of unity to separate the stable and unstable regions. Corresponding characteristic frequency is given in Fig.10b.

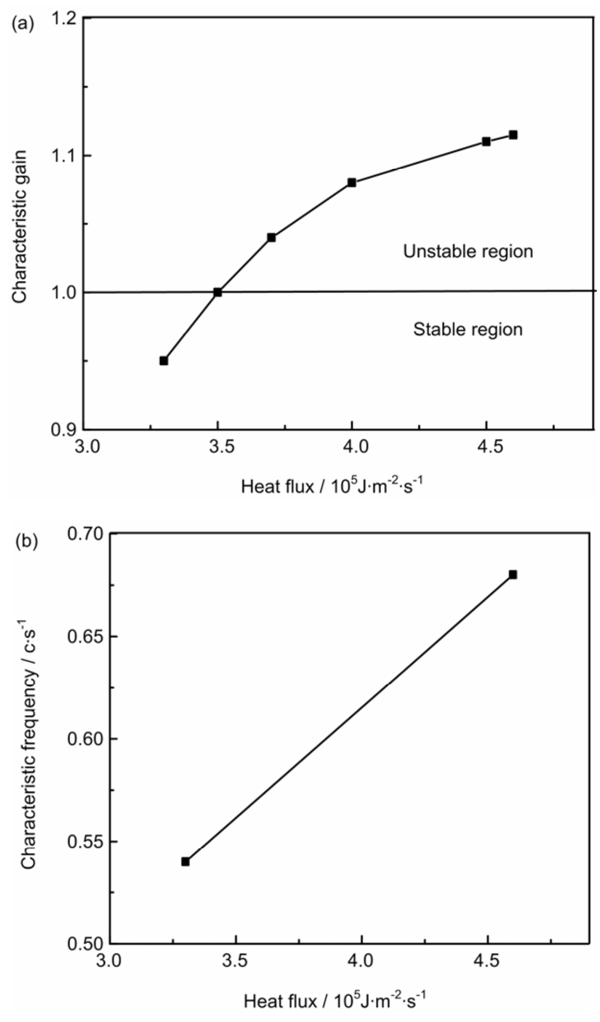

Fig.10 Characteristic gain and frequency in reference to heat flux.

Fig.11 illustrates the curves representing the frequency responses of the gain and shift in oscillation phase under different conditions of the average inlet velocity, inlet temperature, heater length and heat flux. It can be seen that the gain has a general tendency to increase with decreasing frequency, approaching the characteristic frequency. As shown in Fig.10b, the characteristic frequency increases with heat flux, and so does the characteristic gain, not so steeply.

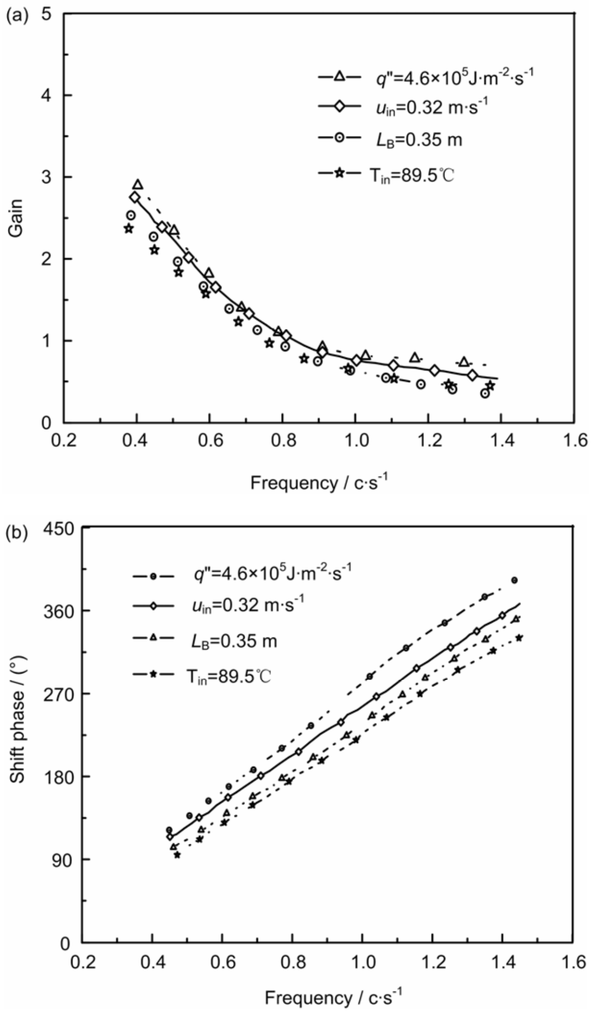

Fig.11 Frequency response shown by gain and shift in phase.

Here a brief summary of the results is as follows:

(1) Increase of the average inlet velocity lowers the gain but does not affect the characteristic frequency, for a given average outlet quality, an intensifying heat flux is accompanied by an increase in the characteristic frequency, and a decrease in the characteristic gain. Consequently, the average outlet quality at the stable boundary tends to rise with increasing average inlet velocity (Fig.5).

(2) With lowering inlet liquid temperature, both the average outlet quality and the gain decrease, but the phase delay increases, bringing marked decrease of the characteristic frequency. These effects interact mutually, resulting in only a slight change in the average outlet quality at the stable boundary in a relatively wide range of temperature (Fig.6).

(3) With shortened heater length, the gain is reduced by the lowered average outlet quality, while the phase delay remains nearly constant. For this reason, for equal average outlet quality, the characteristic frequency increases in keeping with the heat flux, while the gain decreases. Consequently the average outlet quality at the stable boundary increases as the heater length is shortened (Fig.7).

The system tends to become unstable with increasing average outlet quality and with decreasing characteristic frequency.

5 Conclusion

The instabilities observed in through twin parallel channels can be classified into three types, of which only one is intrinsic to parallel-channel systems, being generated through the interaction between the channels. The remaining types of instability occur also in single channel.

The parallel-channel boiling system possesses a characteristic oscillation that is quite independent of the magnitude and duration of the initial disturbance. The stable boundary is influenced by the characteristic frequency of the system as well as by the exit quality when this is low. Upon raising the exit quality and reducing the characteristic frequency, the system increases its instability. Entrance throttling effectively contributes to stabilization of the system. In respect of the amplitude of flow oscillation, a widely applicable quantitative result could not be obtained, but it was indicated that the amplitude ratio tended to augment with increasing departure from the stable boundary into the unstable region. The period of frequency of the flow oscillation is sensitively dependent on the time required by the fluid to pass through the preheating region.

Nomenclatures

C_R: Coefficient of pressure drop due to entrance throttling ($kg \cdot s^2 \cdot m^{-4}$)

D_O: Inner diameter of outer tube (mm)

h': Liquid saturation enthalpy (kJ/kg)

h_{in}: Inlet liquid enthalpy (kJ/kg)

L_B: Single-phase water region length (m)

q'': Heat flux ($kJ \cdot m^{-2} \cdot h^{-1}$)

q''' : Calorific power per unit volume ($kJ \cdot m^{-3} \cdot s^{-1}$)

u_{in}': Average inlet velocity (m/s)

u_{in}: Amplitude of flow oscillation (m/s)

ρ_l: Liquid density (kg/m^3)

Acknowledgment

The authors wish to extend warm acknowledgement to Professor LUO Jijun for his encouragement and helpful discussions.

References

1 Padki M M, Palmer K, Kakac S. Int J Heat Mass Transfer, 1992, **35:** 525–532.

2 Su G H, J D N, K F D. Nucl Eng Des, 2002, **215:** 187–198.

3 Veziroglu T N, Lee S S, Kakac S. Two-Phase Rows Heat Transf, 1997, **1:** 423-466

4 Comakli O, Karsli S, Yilmaz M. Energy Convers Manage, 2002, **43:** 249–268.

5 Ruan Y Q, Fu L Z. Proc IFAC, September 16-18, Philadelphia, 1986, 124–130.

6 Takitani K, Morishita H. J Nucl Sci Technol, 1980, **17:** 393–401.

7 Wu G P, Qiu S Z, Su G H. Nucl Sci Tech, 2007, **18:** 247–250.

8 Aritomi M, Shigebumi A, Akira I. J Nucl Sci Technol, 1977, **1:** 22–30.

9 Hou S X, Zhao F Y, Tai Y. Nucl Power Eng, 2008, **5:** 43–47.