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EXPERIMENTAL INVESTIGATION ON TWO TYPES OF DENSITY-WAVE OSCILLATION IN PARALLEL TWIN RECTANGULAR CHANNELS

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Abstract

An experimental investigation was performed on density-wave oscillation with twin parallel rectangular channels under forced circulation.Both Type I and Type II density-wave instabilities were observed in this experiment.General observations on flow oscillation behavior showed that there were two stable zones separated by two unstable zones during heating. The effects of thermal parameters on the oscillation period of Type I instability and the instability boundary heat flux and quality of two types of instabilities have been investigated in this paper. Finally, dimensionless flow instability boundaries of two types of instabilities were obtained and compared.

1. Introduction

Density-wave oscillation(DWO) is one of the most common dynamic two-phase flow instabilities, which results from multiple feedbacks between flow rate, pressure-drop and the change in density caused by vapor generation in a boiling channel.

Generally, density-wave oscillation could be classified as two types: Type I and Type II instabilities. Type I instability occurs at very low steam quality condition,which is of specific importance in natural circulation reactors. While Type II instability, occurs at relatively high power and low inlet subcooling[1](Durga Prasad,2007).Density-wave oscillation is by far the most studied type of oscillation in two-phase flow instability problems, and the amount of published experimental work in this field is overwhelming.

As early as 1995, Semenovkel[2] (1955) reported the results of experimental studies on two-phase flow instabilities in the Soviet Union during the 1950s. Oscillations were investigated using a multi-channel circulation boiler. Unstable conditions were set by either decreasing the flow rate or by increasing the heat input.

Fukuda and Kobori [3](1979) proposed the classification of DWO based on their investigation on density-wave oscillation on forced and natural circulation conditions in two parallel channels.They also stated that Type I DWO was governed by the gravity and acceleration in the heated channel,while Type II DWO was governed by the friction in heated channel.

An investigation on Type I and Type II BWR stability characteristics are reported by Hagen[4](2000). The Type-I stability boundary was reached; the Type-II stability boundary was crossed. Flashing is shown to be an important phenomenon for driving the coolant flow at start-up conditions and for Type-I stability features.

Nayak(2002) et al.[5] carried out an investigation on the stability behaviour of a natural circulation pressure tube type boiling water reactor. In this study, The stability behaviour of a natural circulation pressure tube type boiling water reactor (BWR) has been investigated analytically. The results indicate that both Type I and Type II density-wave instabilities can occur in the reactor in both in-phase and out-of-phase mode of oscillations in the boiling channels of the reactor. The delayed neutrons were found to have strong influence on the stability of Type I and Type II density-wave instabilities.

Su Guanghui et al. [6](2002)made a theoretical and experimental study of Type I DWO in natural circulation. The influences of mass flow rate, pressure,inlet subcooling, heat flux and exit quality on DWO were analyzed.

Prasad(2008) [7]et al. reported their theoretical study on flow instabilities in double-channel natural circulation boiling systems. The results shows that the two channels oscillate out-of-phase in Type-I region, but in Type-II region, both the modes of oscillation are observed under different conditions.

Although a number of density-wave oscillation studies have been performed experimentally and theoretically by different researchers, most of which are based on round tube, few literature refers to the DWO in rectangular channel. Donghua Lu, et al.[8],(2011) investigated the density wave oscillation with two parallel rectangular channels, which have a cross section of 25 mm×2 mm and a heated length of 1000 mm. Only Type II instability was observed in the experiment. The results show that in general the flow becomes more stable when mass velocity, pressure,and inlet subcooling are increased. The period of oscillation becomes shorter if mass velocity is increased or inlet subcooling is decreased. Pressure has little effect on period of the DWO in this research. The comparison indicates that the data from rectangular channels agree with those from the round tubes.

In present study, both Type I and Type II instabilities were observed in parallel rectangular channels on forced circulation . Instability boundary heat flux and quality of two types of DWO and the oscillation period of Type I instability were investigated through the experiment.

2. Experimental apparatus and method

Experimental apparatus including test loop, test section and motion platform are simply introduced here and the experimental procedure is described.

2.1 Test loop

A schematic of the boiling loop used for this study is shown in Fig.1. It is a closed cycle loop with maximum pressure capability as 16 MPa. The pressure of the loop was stabilized by a pressurizer with nitrogen charged in its upper space.

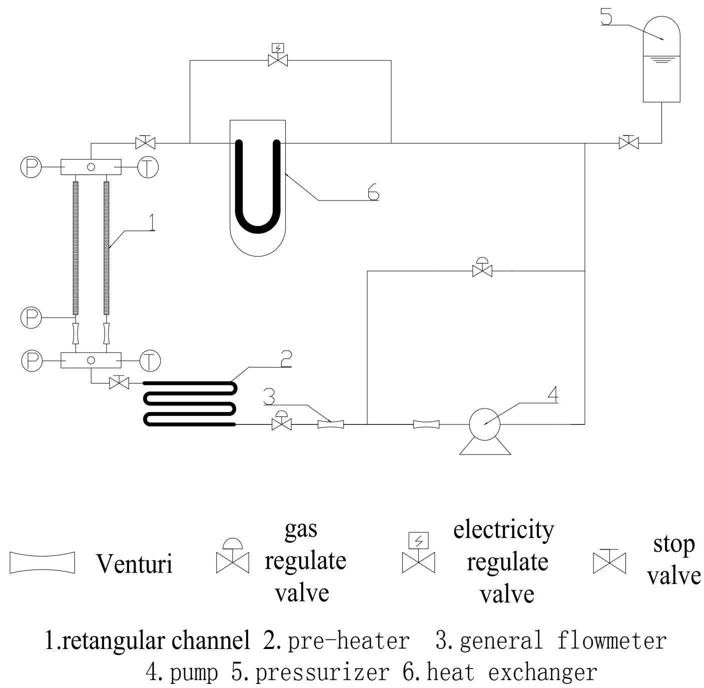


Fig.1. Schematic diagram of test loop.

Demineralized and degasified water was chosen as the operating fluid. It was fed into the boiling loop by a plunger pump. Two gas regulate valves, installed separately on the bypass (GV1) and the test branch(GV2), controlled the flow rate through the test section. A direct electrical-heating preheater was used to regulates the liquid temperature at the inlet of the heated test section. Two-phase mixture flowing out of the test section was chilled by a heat exchanger, where the temperature of fluid could be condensed to below 40℃.

2.2 Test section

The test section was composed of two 1000mm long, parallel rectangular channels made of 0Cr18Ni10Ti stainless steel plate with a cross section of 50mm×2mm(Fig.2). Each side of the heating plate had the same thickness of 3 mm.

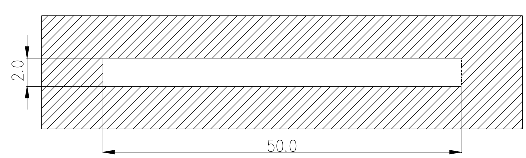


Figure 2 Cross section of rectangular channel(mm).

2.3 Measurement and uncertainty

Simple instruments have been used for real-time measurement of flow rate, temperature, pressure and power to test section. Three Venturi flowmeters were used to measure the flow rate into the lower plenum and through the two parallel channels. Venturi flowmeter was chosen for it's good performance at high pressure and temperature. The pressure transmitter had short response time and 1000 Single/s sampling capability to match the frequency of pressure difference oscillation in flowmeters. The accuracy of flow measurement was about ±1% of the full-scale flow.

Two Honeywell test gauge with accuracy of ±0.1% were installed to measure the pressure at the inlet and outlet of the test section. The inlet pressure was considered the system pressure for data analysis. The pressure drop across the inlet section and exit section were measured with two ST3000 type pressure differential pressure transmitters of range 0~0.1MPa with accuracy of ±0.1% of full-scale pressure drop.

Armored chromel-constantan immersion thermocouples were used to measure fluid temperature at the inlet and exit of the heated test section. A typical uncertainty associated with temperature measurement was 1℃.Besides,12 K-type thermocouples were welded on the surface of channels at the top of test section to monitor the temperature excursing in the event of severe dry out.

Power to the heated test section was obtained by measuring the current into the test section and the voltage drop across the heater. The electrical current was measured with a digital multimeter and the voltage drop across the heater tube was measured with a multi-range voltmeter. Maximum uncertainty in power measurement was about ±1% of measured power.

Table 1 shows the ranges of thermal parameters of this experiment.

Table 1. Range of thermal parameters

No.	Parameter	Range
1	P(MPa)a	2.0~8.0
2	G(kg/m2s)b	200~500
3	ΔTsub(℃)c	40~140

a: P refers to system pressure;
b:G refers to the average mass velocity of two channels;
c: ΔTsub refers to the inlet subcooling of flow.

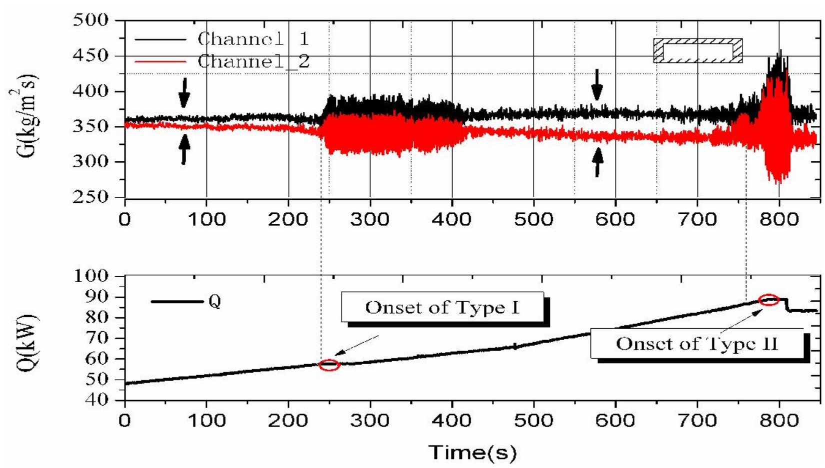
3. Results and discussion

3.1 General observation

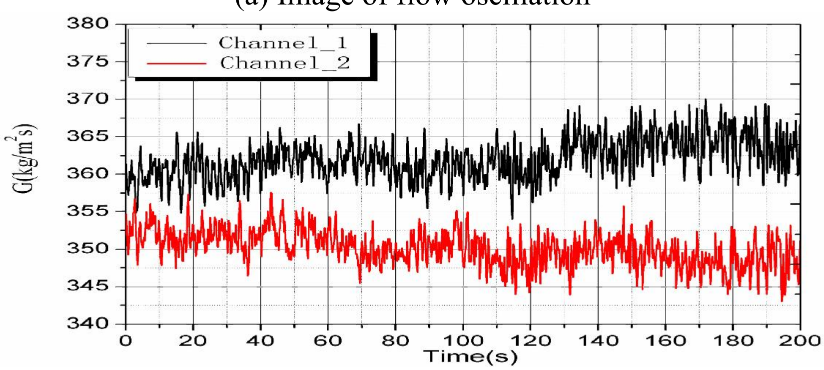
Fig.3 shows the general observation of flow oscillations of Type I and Type II instabilities. It can be seen from Fig.3(a) that the heat power at the onset of two types of instabilities are very different. Type I instability occurs with lower heat power(54kW) and Type II instability occurs with higher heat power(86kW).Considering the two types of instability occurs under the same operating condition, the boundary quality of Type I DWO is much lower that that of Type II DWO.

From the picture, it's very clear that there are two stable zones being separated by two unstable zones. In the first "stable zone" (Fig.3(b)), flow is basically stable except for those small random oscillation, where heating power is lower than the boundary heating power at the onset of Type I instability. In the second "stable zone", the amplitude of random flow oscillation increase (Fig.3(d)), and in this zone, flow excursion could be observed in parallel channels, which is a typical phenomena of Ledinegg instability. Ledinegg flow instability is one of static two-phase flow instability, which generally occurred in negative slop region of internal characteristic curve.

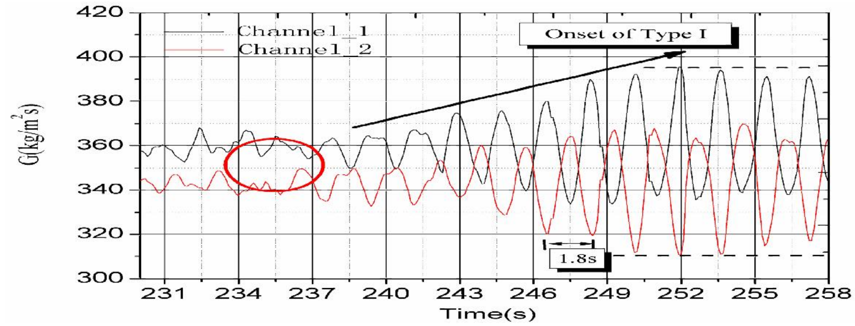
It can also be seen that the flow oscillation behaviors of two types of instabilities have some differences.The most obvious one is that the amplitude of Type I DWO is relatively small and it is nearly invariable throughout the whole unstable zone, but the amplitude of Type II DWO is much larger and grows very quickly after the heating power cross the stability boundary. The largest amplitude of Type II DWO could be as high as 80~90 percent of average flow rate under some operating condition.



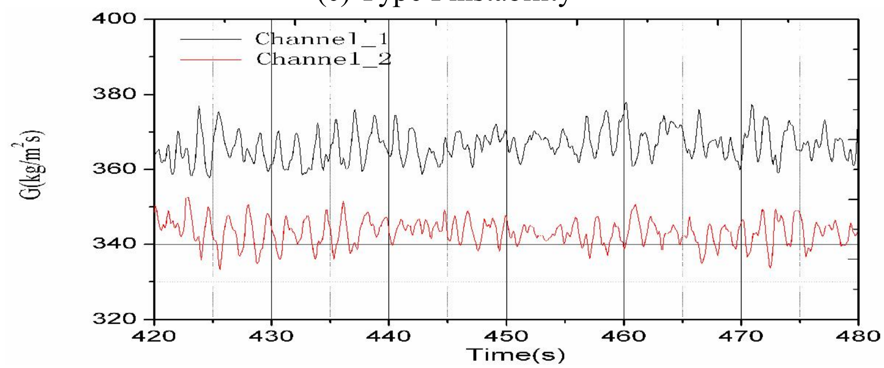
(a) Image of flow oscillation



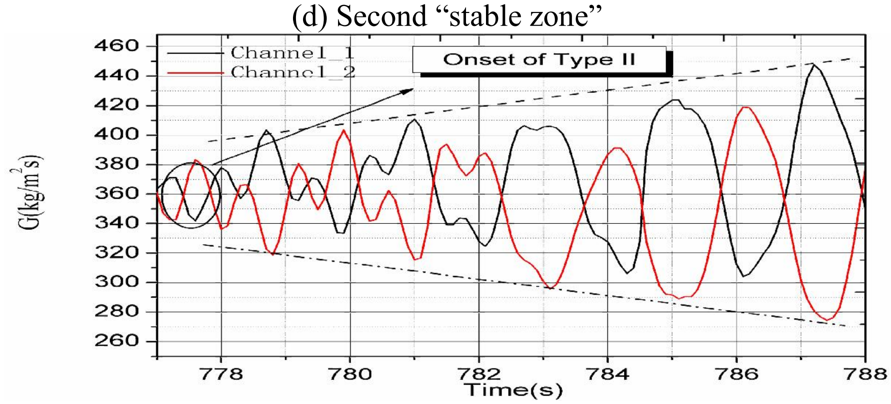
(b) first "stable zone"



(c) Type I instability



(d) Second "stable zone"



(e) Type II instability

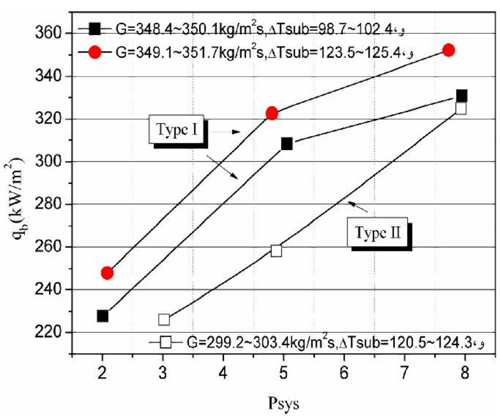
Fig.3 General observation of Type I and Type II instabilities

3.2 Boundary heat flux and boundary exit quality

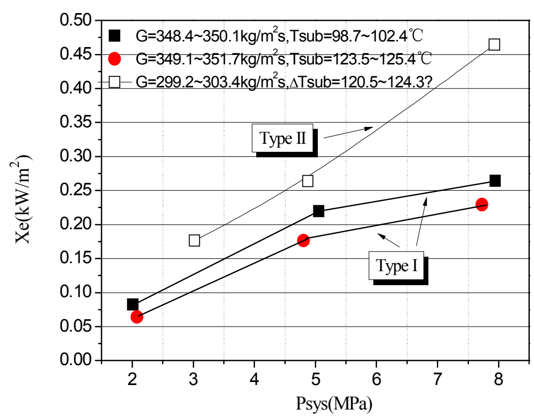
Boundary heat flux q_b and boundary exit quality Xe_b are two significant indexes for evaluating the flow instability of system. Boundary heat flux refers to the heat flux into the test section obtained from the heated wall at the flow instability boundary, and boundary quality refers to the steam quality of flow at the exit of channel at the boundary of flow instability.

3.2.1 Effect of system pressure

Effects of system pressure on the boundary heat flux and boundary quality of Type I and Type II instabilities are shown in Fig.4. It can be seen that q_b and Xe_b of both Type I and Type II instabilities are increased with improved system pressure. The simple explanation is that: as system pressure is increased, density of flow and density difference of two phases get smaller.The decreased density of flow causes a lower gravitational pressure drop and the decreased density difference of liquid and vapor leads to the decrease of acceleration and two-phase frictional pressure drop in heated section. Since the gravitational and acceleration pressure drop are generally regarded as the driving force of Type I DWO and the two-phase frictional pressure drop are considered as the driving force of Type I DWO,it's reasonable to see the two-phase system is more stable at higher pressure.



(a) heat flux



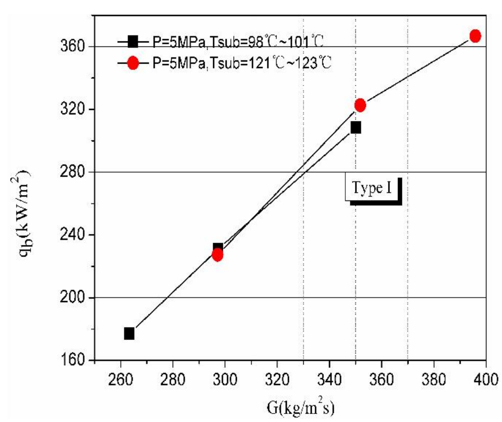
(b) quality

Fig.4 Effect of System pressure on q_b and Xe_b

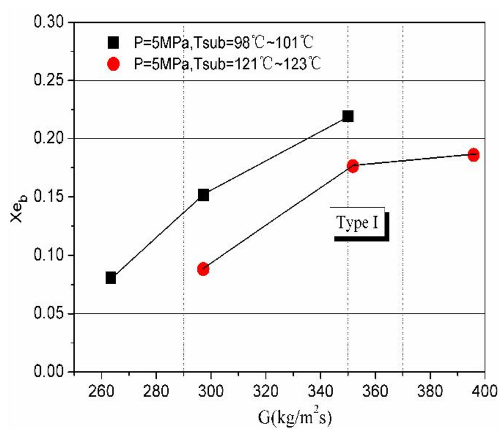
3.2.2 Effect of mass velocity

Effect of system pressure on the boundary heat flux and boundary quality of Type I is shown in Fig.5. It indicates that both q_b and Xe_b of Type I instability increase as the mass velocity is increased, which means the occurrences of Type I DWO is more difficult at higher mass velocity.

As mass velocity increase, two basic changes related to DWO would happen.The one is that the acceleration pressure drop is increased with the increase of mass velocity($\Delta P_a \propto G$), as it's stated above, it is helpful to the occurrence of Type I DWO. The second change is that the frictional pressure drop of flow increases, and its increasing speed is much higher ($\Delta P_f \propto G^2$). Since the quality of flow is very low as Type I DWO occurs,the increase of frictional pressure drop concentrate in single-phase section. Generally, a larger single-phase frictional pressure drop could impede the occurrence of flow oscillation. Considering the increasing speed of frictional pressure drop is higher, the increases of boundary heat flux and boundary quality are understandable.



(a) boundary heat flux



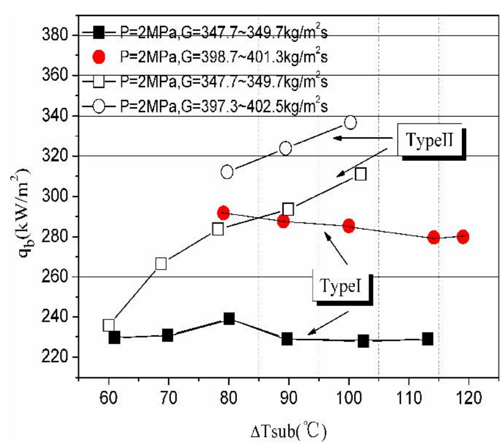
(b) boundary quality

Fig.5 Effect of mass velocity on q_b and Xe_b

3.2.3 Effect of inlet subcooling

Effects of system pressure on the boundary heat flux and boundary quality of Type I and Type II instabilities are shown in Fig.6. It can be seen from the pictures that the changes of q_b and Xe_b of Type I and Type II instabilities are very different. In fact, the explanation for these changes are also different. First of all, for Type I instability, q_b seems insensitive to the change of ΔT_{sub},while Xe_b decreases quickly with the increase of ΔT_{sub}.Let us concentrate on the change of Xe_b, as inlet subcooling increase, the density difference of inlet flow and outlet flow get larger. It would directly result in the increase of acceleration pressure drop, since acceleration pressure drop in heated section is the main driving force of Type I DWO,the decrease of Xe_b is reasonable. As for the change of q_b, because the decrease of Xe_b just makes up the decrease of the inlet enthalpy with increased ΔT_{sub},its change is not obvious.

Scond, for Type II DWO,the increased ΔT_{sub} has limited effect on its driving force (two-phase frictional pressure drop) or inhibition effect(single-phase frictional pressure drop). So the change of Xe_b is not very big. The reason for the increase of q_b mainly results from the decrease of inlet enthalpy with increased ΔT_{sub}.



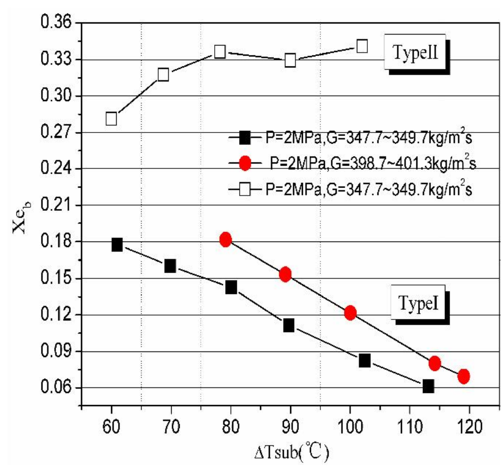


Fig.6 Effect of inlet subcooling on q_b and Xe_b

3.3 Period of flow oscillation

Period is another important characteristic parameter for flow oscillation. It's believed that the period of DWO is proportional to the time of the flow passing through the channel("passing time"). In present study, periods of Type I instability were obtained based on the data analysis, on the whole, it ranges from 1.3s to 2.8s throughout the operating conditions. The effects of thermal parameters on oscillation period are shown in Fig.7,Fig.8 and Fig.9.

It can be seen from Fig.7, the changes of system pressure have little effect on the periods of Type I DWO in this experiment. In fact ,the system pressure majorly influence the physical property of two-phase mixture. At higher pressure,with the same quality, the two-phase mixture of unit volume is heavier and the speed of two-phase mixture should be faster and the "passing time" would increase. But in fact, boundary quality of Type I DWO is not unchanged, in fact, it is increased with the increased pressure(as shown in Fig.4(b)), which offsets the effect caused by the increase of pressure. Therefore, the change on the density of flow is limited and the period of flow oscillation changes little with the increase of system pressure.

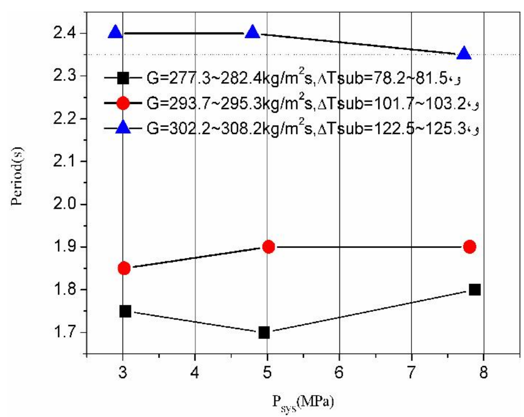


Fig.7 Effect of pressure on the period of Type I instability

As shown in Fig.9, oscillation period of Type I instability decrease quickly with the increase of mass velocity. There are two major reasons, first, the speed of single-phase flow was increased when mass velocity increase.Second, the increase of boundary quality with increased mass velocity (as shown in Fig.5(b) lead to the increase of the speed of two-phase flow. Therefore, the speed of single-phase flow and two-phase mixture both increase as mass velocity is increased, which causes the reduction of "passing time" and the period of flow oscillation.

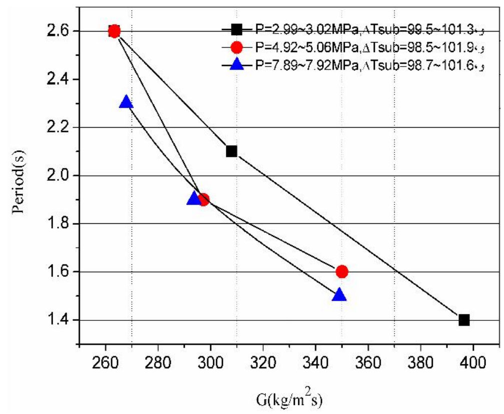


Fig.8 Effect of mass velocity on the period of Type I instability

Fig.9 shows the effect of inlet subcooling on the oscillation period. From the picture, it can be seen that the oscillation period increases as the inlet subcooling is increased. The major reason is that Xe_b decreases quickly with increased inlet subcooling(as shown in Fig.6(b)). With the decrease of exit quality, two-phase flow becomes denser and its flow speed would be slower, so the "passing time"and oscillation period will increase accordingly.

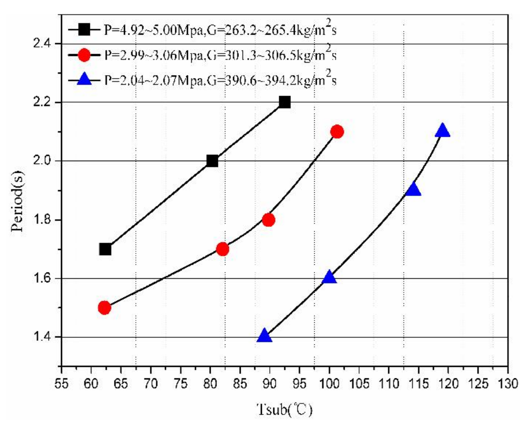


Fig.9 Effect of subcooling on the period of Type I instability

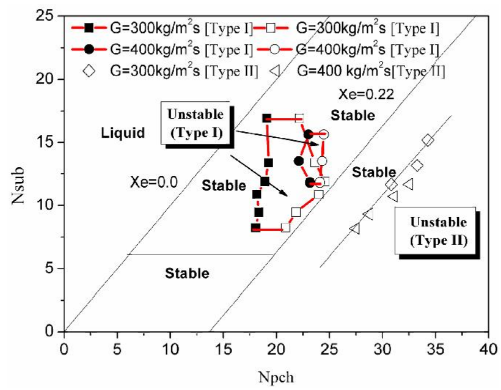
3.4 Dimensionless instability boundary (Npch-Nsub)

Dimensionless subcooling number Nsub and phase change number Npch are widely used to describe the flow instability regime. Fig.10 shows the stable and unstable zones of Type I and Type II instabilities in space of Npch-Nsub at the pressure of 3MPa and 8MPa.Definitions of the dimensionless inlet subcooling number Nsub and phase change number Npch are:

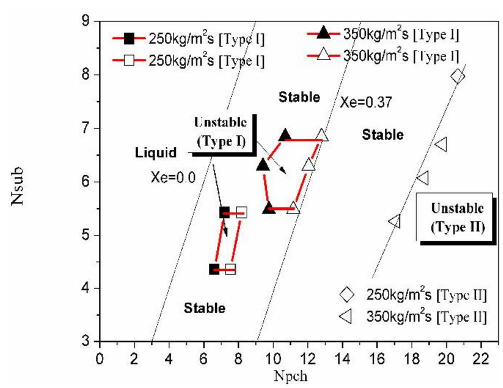
$$N_{sub} = \frac{\Delta h_{in}}{h_{fg}} \frac{\Delta \rho}{\rho_g} \quad (1)$$

$$N_{pch} = \frac{qA_H}{Gh_{fg}A_F}\frac{\Delta\rho}{\rho_g} \qquad (2)$$

Here, Δh_{in} -inlet subcooling enthalpy (kJ/kg); $\Delta\rho$ -density difference of saturated gas–liquid (kg/m^3); h_{fg} -vaporization enthalpy (kJ/kg); ρ_g -gas density (kg/m^3); q -heat flux(kW/m^2); G-mass velocity (kg/m^{2}s); A_H -area of channel cross section(mm2); and A_F -heating surface (m^2).



(a) P=3MPa



(b) P=8MPa

Fig.10. Flow instability boundary of Type I and Type II instabilities

From the pictures, it is very clear that the shape and position of unstable zones of two types of density-wave instabilities are very different. First , the unstable zones of Type I instability lie in the low Npch area, while the unstable zones of Type II instability lie in relatively higher Npch area.Second,unstable zones of Type I DWO have two boundary points corresponding to a value of Nsub, the two boundary lines make the unstable zone a closed region.On the contrary, the boundary points of Type II DWO is not multi-valued and its unstable zones are more open and much wider.Third, the position and shape of unstable zones of Type I DWO change a lot as mass velocity is changed,which make it hard to predict the unstable zones of Type I DWO. One the contrary, the instability boundaries of Type II DWO with different mass velocity are nearly overlapped each other.Based on the experimental data, a predication criterion of instability boundary of Type II DWO is corelated and given in eq.(3):

$$Nsub = 0.8Npch - 14.5 \qquad (3)$$

4. Conclusion

In this paper, Type I and Type II density-wave flow instabilities have been experimental investigated with twin parallel rectangular channels under forced circulation. Through the experiment, several conclusions have been obtained,which are listed as follows:

1) For one operating condition, two types of instability occur with different heat flux. Among which, the Type I DWO occurs with low boundary heat flux and quality. The observation indicates there is transition zone between the unstable zone of two types of DWO.

2) Oscillation behaviors of two types of instabilities are different: the amplitude of Type I DWO is relatively small and nearly invariable throughout the unstable zone, while the amplitude of Type II DWO is much larger and grows very quickly after the heating power cross the stability boundary.

3) Oscillation period of Type I instability decreases as mass velocity is increased but increases as inlet subcooling is increased. The change of pressure has little effect on period of Type I DWO in this experiment.

4) As system pressure and mass velocity are increased, q_b and Xe_b of Type I instability is increased;As inlet subcooling is increased, Xe_b of Type I instability was decreased, but the q_b is not obviously affected.

4) As system pressure and inlet subcooling are increased , q_b and Xe_b of Type II instability is increased;As mass velocity is increased, q_b of Type II instability is increased while Xe_b is decreased.

5) Unstable zones of Type I instability are closed regions whose positions and shapes change a lot as mass velocity is changed. On the contrary, the instability boundary of Type II DWO with different mass velocity are nearly overlapped with each other .

5. References

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