Int. J. Multiphase Flow Vol. 19, No. 1, pp. 65–77, 1993
Printed in Great Britain

0301-9322/93 \$6.00 + 0.00
Pergamon Press Ltd

A MULTIVARIABLE LINEAR INVESTIGATION OF TWO-PHASE FLOW INSTABILITIES IN PARALLEL BOILING CHANNELS UNDER HIGH PRESSURE

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(Received 22 June 1991; in revised form 25 May 1992)

Abstract—This paper presents experimental results as well as an analytical model of density-wave instability in parallel boiling channels under high pressure. The experiments have been performed on a high-pressure steam–water loop. Different types of two-phase flow instabilities have been observed, including density-wave (DWO), pressure drop, thermal and second density-wave (2nd DWO) oscillations. The 2nd DWO appears at a very low exit steam quality (approx. <0.1) and in the positive portion of the ΔP–G curves with both channel flow rates oscillating in phase. The DWO can appear at pressures up to 192 bar and disappears above 207 bar. A multivariable linear model is developed to analyse the system stability in the frequency domain by means of multivariable control system theory. The multichannel boiling system is expressed by transfer matrix models which include feedback on the two-phase pressure drop and external loop pressure drop. A computer program, DENSITY-PARA, is coded for the stability analysis of a parallel boiling channel system with or without cross-connection. Using this model, the effect of the main parameters on the system stability can be analysed conveniently.

Key Words: two-phase flow, instability, density-wave oscillation, boiling, parallel channels, experiment, analysis

1. INTRODUCTION

Two-phase flow instabilities in parallel boiling channels have been studied both experimentally and theoretically in the past few decades because of their importance in the safety of boilers, boiling heat exchangers, BWRs, steam generators of fast breeder reactors and LMFBRs. Such systems are susceptible to dynamic instabilities of various types, such as flow excursions and flow oscillations (Bergles 1981; Stenning & Veziroglu 1965; Kakac & Veziroglu 1983). Two-phase flow instabilities can cause formidable problems, such as tube thermal fatigue, flow-induced structure vibration, degradation of performance and deterioration of system control.

Most of the previous studies on two-phase flow instabilities in parallel boiling channels were carried out on a Freon loop or a low-pressure steam–water loop and the parameter ranges were limited (Clowley *et al.* 1967; D'Arcy 1967; Lee *et al.* 1977; Aritomi *et al.* 1977; Nakanishi *et al.* 1983); however, studies of two-phase flow instabilities in parallel boiling channels under pressures up to subcritical (i.e. near 200 bar) are very rare, and such quantitative experimental data are very limited. For instance, what are the upper pressure limits for the existence of density-wave oscillation (DWO) and second density-wave oscillation (2nd DWO)? Does DWO always appear after the occurrence of a pressure-drop-type oscillation (PDO) in parallel boiling channels? Can we judge the start of DWO in parallel boiling channels only by the oscillation of the total flow rate? Can a PDO exist without an upstream surge tank? In this paper, we give not only the answers to these questions but also the quantitative experimental data.

The authors have performed experiments of two-phase flow instabilities in parallel boiling channels on a high-pressure steam–water loop under pressures up to 207 bar. The main parameter effects on two-phase instabilities, such as pressure, mass flow rate and inlet subcooling, were studied. In addition, the authors studied the effects of unbalanced heating between parallel channels on the stabilities and found important results. In most cases, the more severe the unbalanced heating, the more stable the parallel boiling channel system.

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Several types of two-phase flow instabilities were observed: (1) on-boiling instability; (2) 2nd DWO; (3) DWO; (4) PDO; and (5) thermal oscillation; in which the 2nd DWO appears in the positive portion of the flow characteristic curve (ΔP–G), hence its name, but only at very low exit steam quality (approx. <0.1). This paper mainly discusses the 2nd DWO and DWO in parallel boiling channels under high pressure.

The most frequent dynamic instability is DWO and it has been studied extensively. Most analyses in the past have been for a single channel. Some researchers have studied DWO in parallel boiling channels (Davies & Potter 1967; Fukuda & Kobori 1978; Fukuda & Hasegawa 1979; Romberg 1984; Taleyarkhan *et al.* 1986), most of whom neglected some important factors, such as the conjunction between the channels, the connection between the channels and the external loop, the channel wall dynamics, thermodynamic non-equilibrium, flow condition differences between the two phases, etc.

The authors present an analytical model of DWO in parallel boiling channels with or without cross-connection. Based on the drift-flux model, this analysis accounts for thermodynamic non-equilibrium, heater wall dynamics, arbitrary flow paths for cross-connection, etc. The analysis is in the frequency domain, and a multiinput, multioutput Nyquist stability criterion is used to estimate the stability of the multivariable multichannel system with or without cross-connections.

2. EXPERIMENTAL RESULTS

2.1. Experimental system

The high-pressure steam–water two-phase flow experimental rig is situated in the Multiphase Flow and Heat Transfer Laboratory of Xi'an Jiaotong University.

A schematic diagram of the forced-convection high-pressure steam–water loop is shown in figure 1. This loop can conduct thermo-hydrodynamic experiments under a pressure range of about 30–300 bar, with flow up to 5 ton/h and a heating capacity up to 900 kW. In this parallel boiling channel instability experiment, the parameter ranges are (P—pressure, G—mass velocity, ΔT_{sub}—inlet subcooling):

$P = 30$–207 bar, $G = 500$–$1200\ \mathrm{kg/s \cdot m^2}$ (for each channel)
$\Delta T_{sub} = 10$–$100°\mathrm{C}$, $q_{min}/q_{max} = 0$–1
Length of the test section, $L = 9.04$ m
Diameter of the channel, $D = 12$ mm
Thickness of the tube, $\delta = 2$ mm
Number of the channels, $N = 2$

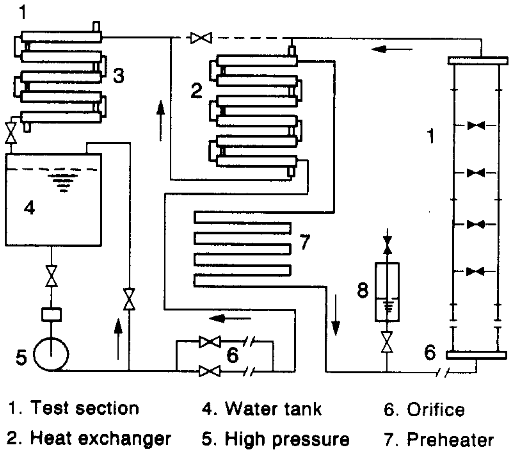

Figure 1. High-pressure steam–water loop and test section.

The test sections were made of stainless steel. They were heated directly and separately by two a.c. (low voltage, high current) transformers with a capacity of 180 kW each. The capacity of the preheaters is 560 kW.

The experiments were conducted by increasing the wall heating, while keeping the pressure, mass flow rate and inlet subcooling almost constant to obtain different types of two-phase flow instabilities. All the signals were connected to the computer (via Solartron' data collecting units for steady-state data collection and MS-1215 fast data collecting units for dynamic data collection) for storage, printing and analysis. Multipen data recorders were also used for direct signal recording. A 14-channel dynamic analogue signal tape recorder was used for signal spectron and transfer function analysis. This paper discusses the experimental results without cross-connections.

2.2. Second density-wave oscillation (2nd DWO)

Little data have been reported for this type of instability expecially in the higher pressure range.

The 2nd DWOs were observed for a wide range of parameters. It is called the 2nd DWO because, like the DWO, it appears in the positive portion of the characteristic curve (ΔP–G). However, it is different from the DWO in that it appears at a very low exit steam quality (approx. <0.1) and the flow rates in both channels oscillate in phase (they are out of phase for DWO). It appears a little after the on-boiling instability. Figure 2 shows a typical 2nd DWO. When the 2nd DWO occurs the inlet flow rate and the channel pressure drop oscillate in phase. The magnitude of the 2nd DWO is about 20–50% of the static flow rate.

The difference between on-boiling instability and the 2nd DWO is that the former is often irregular and non-periodical or of longer period (e.g. 200 s), while the latter is regular and periodical (about 6–12 s). The positions where the 2nd DWO starts on the (ΔP–G) curve are illustrated in figure 3.

The period and amplitude of the 2nd DWO depend on the system parameters and the existence of a surge tank, as well as the arrangement of the test section or even the loop itself. In this experiment the 2nd DWO appears at all mass flow rates and all inlet subcooling ranges under pressures up to 100 bar. The surge tank contributes significantly to the amplitude and period of the 2nd DWO. The larger the compressible volume, the larger the oscillation amplitude.

After the start of on-boiling, the 2nd DWO appears (sometimes it coexists with the on-boiling instability) and reaches its climax at an exit steam quality of about 0.05–0.1. Then, with increasing wall heat flux, the 2nd DWO becomes weaker and weaker, and gradually disappears. In some cases, the PDO instability occurs after the disappearance of the 2nd DWO. While in other cases, there is a conjunction of the 2nd DWO and the PDO instability.

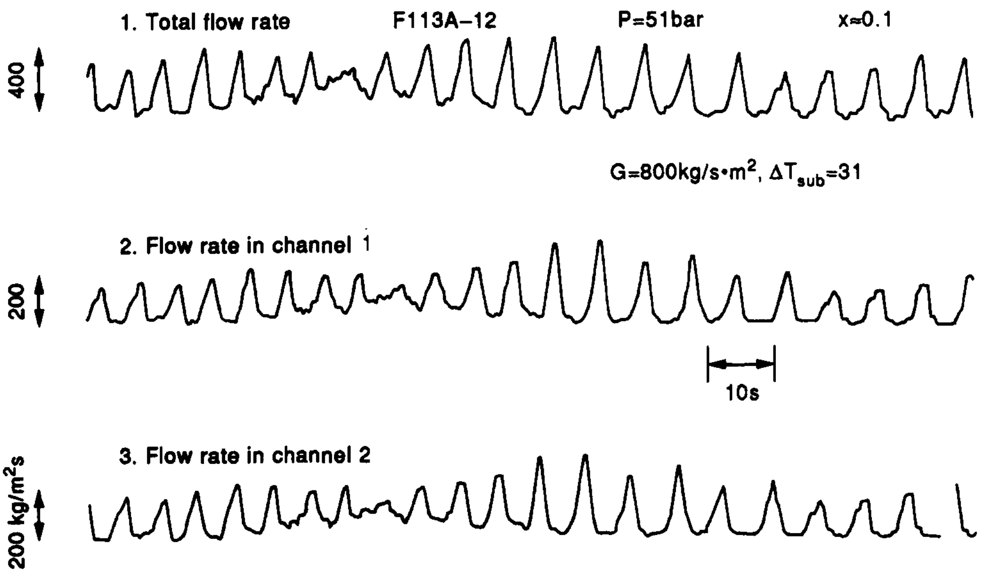

Figure 2. 2nd DWO.

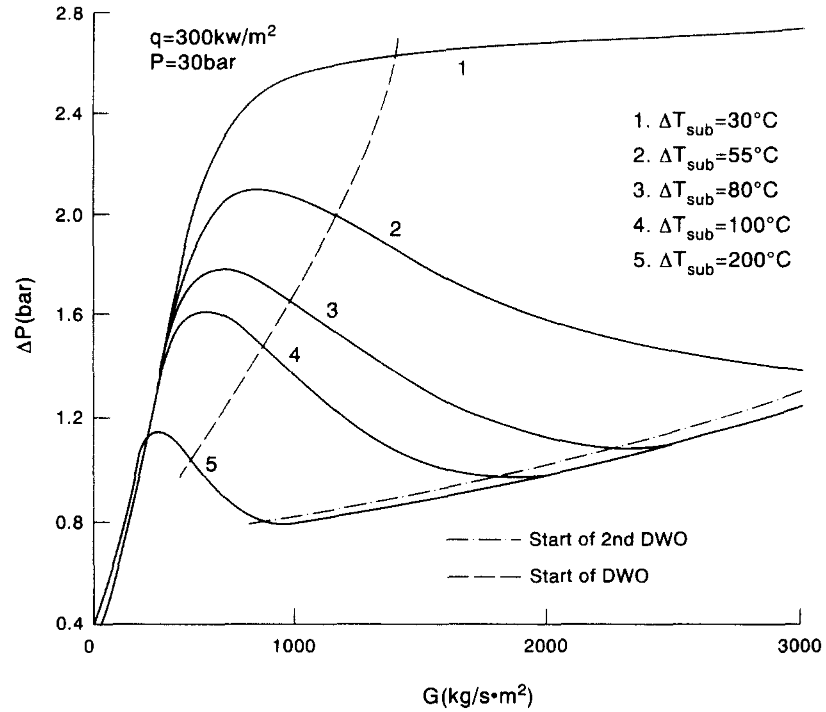

Figure 3. Start of the 2nd DWO on ΔP–G curves.

2.3. Density-wave oscillation (DWO)

The DWO in parallel boiling channels takes place more easily than in single channels over a wide pressure range. Moreover, in the case of balanced heating between channels, there exists only out-of-phase oscillation, and the DWO happens more easily than in the case of unbalanced heating. The magnitude of the flow rate oscillation in an individual channel can be several times larger than that of the total flow rate, which remains almost constant. So, the start of the DWO in parallel

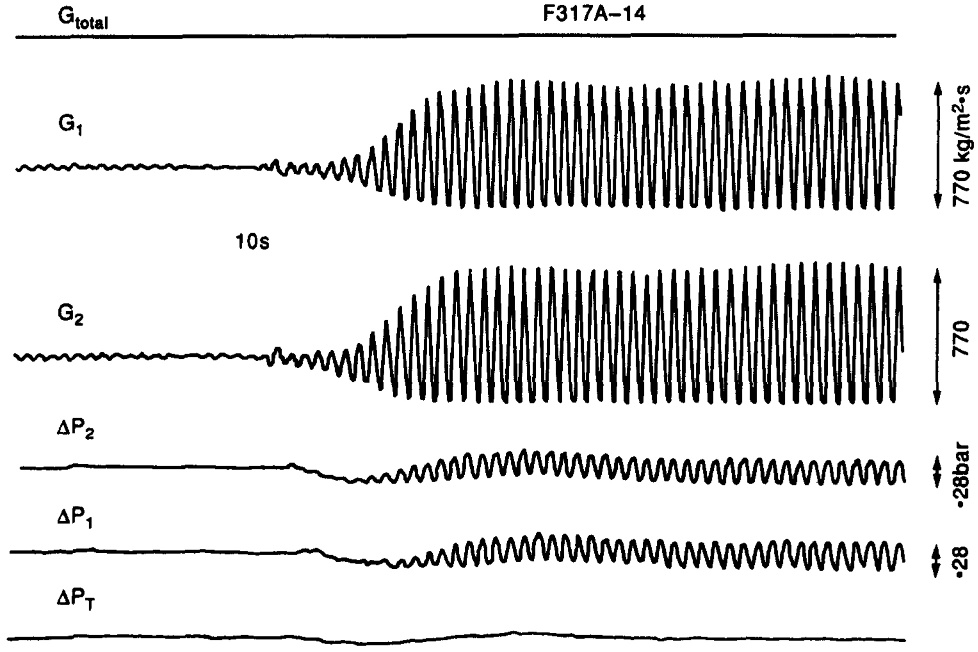

Figure 4. Start of the DWO in parallel boiling channels.

boiling channels, shown in figure 4, is judged by the individual channel flow rate oscillation, and the threshold parameters are recorded and regarded as the instability boundaries. The fully developed DWO is shown in figure 5, in which the magnitude of the oscillation in each channel is about twice as large as its steady flow rate.

For the above reasons more attention should be paid to the study of DWO in the nuclear and power industries, such as the DWO in the secondary side of the steam generator in a PWR nuclear power station, the flow rates of which are only measured at the inlet (feedwater) and outlet (steam). Although the flow rates of the feedwater or steam look stable, intensive DWO may occur in the steam generator. Thus, heat flux oscillation and tube vibration would be induced. For instance, the steam generator tube break incident at Mihama No. 2 Unit (in Japan), on 9 February 1991, was directly caused by fluid-induced vibration, to which, in our view, the large-amplitude DWO between the tube bundles contributed significantly.

In cases with large heat flux, when the flow rate in one channel oscillates at its highest level, the flow rate in the other channel often oscillates backwards (counterflow), with the total flow rate remaining almost constant, shown in figure 6. The magnitude of the oscillation can be more than twice the total flow rate.

In most cases, the DWO takes place after the PDO appears or even after the disappearance of the PDO. However, under certain conditions (lower P and ΔT_{sub}), the DWO can appear before the PDO in parallel boiling channels.

The DWO were observed at all mass flow rates and inlet subcooling in the experimental parameter ranges, at pressures up to 192 bar. However, the DWO no longer appears, in this experiment above 207 bar, when the exit steam was heavily superheated ($x = 1.8$). The typical DWO boundaries are shown in figure 7.

The amplitude and period of the DWO depend on the system operating conditions (pressure, flow rate, inlet subcooling) and the existence of surge tank (compressible volume).

For the situation of unbalanced heating between the channels, the results are interesting and certain. When the DWO takes place, the total flow rate is no longer constant if unbalanced heating exists. The lower the unbalanced heating ratio (Q_{min}/Q_{max}), the more stable the parallel boiling channel system. The comparison of the DWO boundary with balanced and unbalanced heating is shown in figure 8. More experimental results will be published elsewhere.

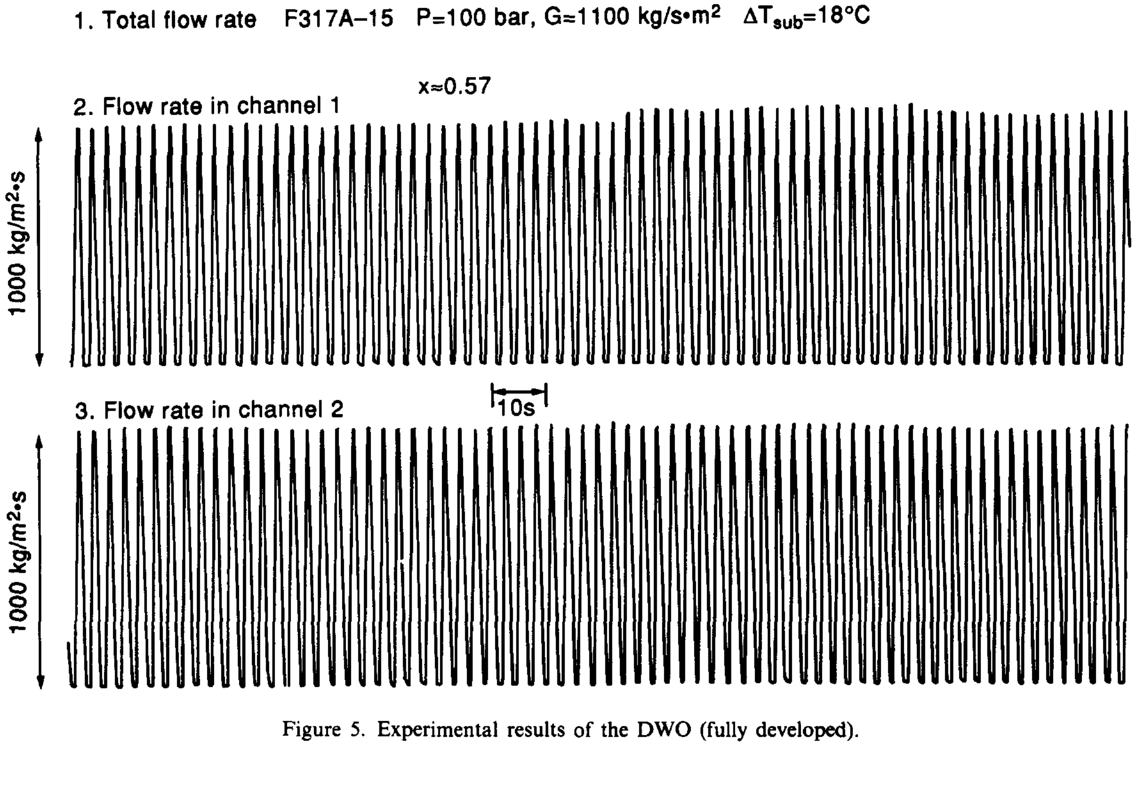

Figure 5. Experimental results of the DWO (fully developed).

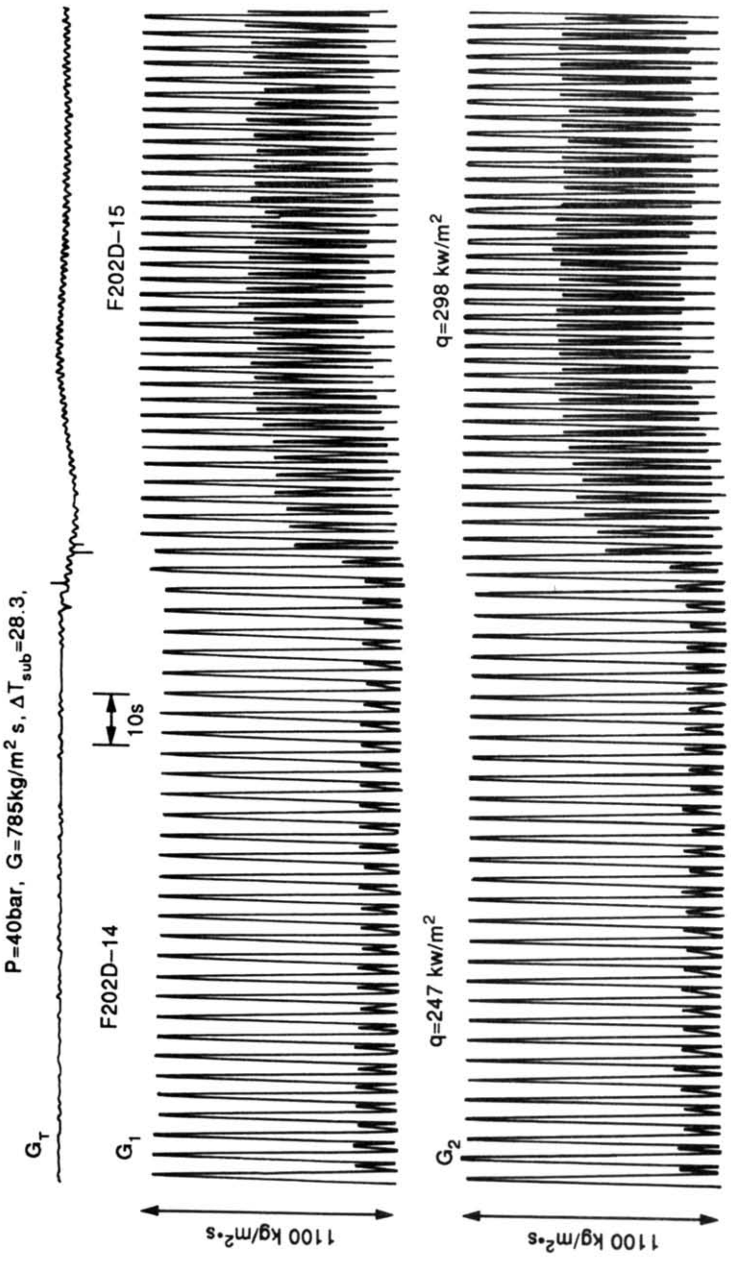

Figure 6. DWO in parallel boiling channels with counterflow.

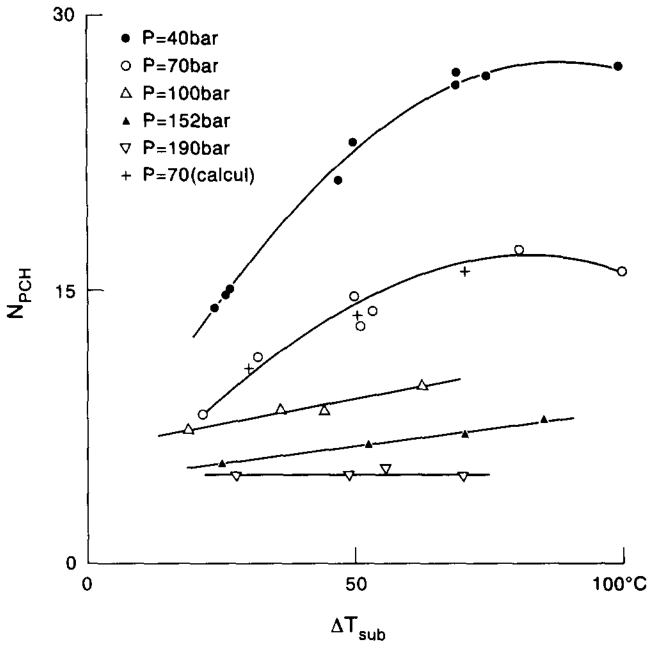

Figure 7. Experimental results of the DWO boundary.

3. ANALYSIS

3.1. Transfer matrix and characteristic function

The multichannel boiling system can be expressed by the transfer matrix model shown in figure 9. The closed-loop transfer matrix is (Xiao *et al.* 1990):

$$\mathbf{H}_{\mathrm{T.M}} = [\mathbf{I} + \mathbf{H}_{\mathrm{test}}^{-1}\mathbf{H}_{\mathrm{loop}}]^{-1}\mathbf{H}_{\mathrm{test}}^{-1}$$
$$= \mathbf{H}_{\mathrm{test}}^{-1}[\mathbf{I} + \mathbf{H}_{\mathrm{loop}}\mathbf{H}_{\mathrm{test}}^{-1}]^{-1}. \quad [1]$$

Thus,

$$\mathbf{H}_{\mathrm{T.M}}^{-1} = \mathbf{H}_{\mathrm{test}} + \mathbf{H}_{\mathrm{loop}}, \quad [2]$$

where $\mathbf{H}_{\mathrm{test}}^{-1}$ is the forward transfer matrix and $\mathbf{H}_{\mathrm{loop}}$ is the external loop feedback transfer matrix.

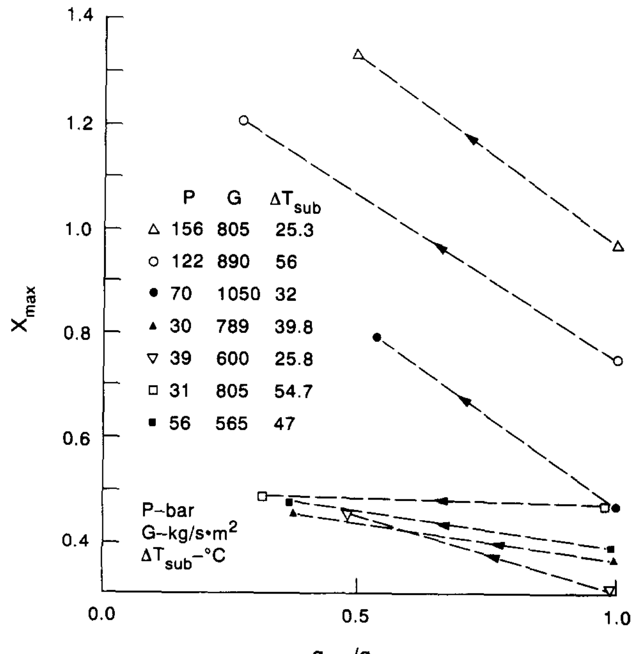

Figure 8. Effect of unequal heating on the DWO boundary.

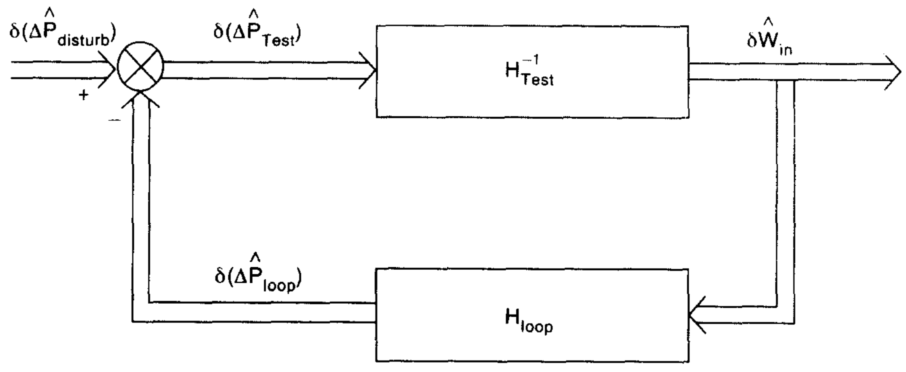

Figure 9. System transfer matrix model.

The return difference matrix can be written as

$$\mathbf{R} = \mathbf{I} + \mathbf{H}_{loop}\mathbf{H}^{-1}_{test} = \mathbf{H}^{-1}_{T.M}\mathbf{H}^{-1}_{test}. \qquad [3]$$

The determinant of which is

$$\det \mathbf{R} = \frac{\det[\mathbf{H}^{-1}_{test}]}{\det[\mathbf{H}_{test}]} = \frac{\det[\mathbf{H}_{test} + \mathbf{H}_{loop}]}{\det[\mathbf{H}_{test}]}$$
$$= \frac{1}{\prod_{i=1}^{N} H_i}\left(\prod_{i=1}^{N} H_i + H_{loop}\sum_{i=1}^{N}\prod_{\substack{i=1\\ j\neq i}}^{N} H_j\right). \qquad [4]$$

The closed-loop characteristic polynomial is given by

$$P_{closed}(s) = P_{open}(s)\det \mathbf{R}. \qquad [5]$$

If $P_{open}(s)$ and $\Pi_{i=1}^{N} H_i$ have no unstable roots and poles (as is the case, usually), the characteristic equation takes the following form (for $N = 2$):

$$H_1H_2 + H_{loop}(H_1 + H_2) = 0. \qquad [6]$$

In the case of total flow rate W_t = const. (thus, $H_{loop} = \infty$), there exists, if any, channel-to-channel instability; and the characteristic equation becomes

$$\sum_{i=1}^{N}\prod_{\substack{j=1\\ j\neq i}}^{N} H_i = 0. \qquad [7]$$

For $N = 2$, it is

$$H_1 + H_2 = 0. \qquad [8]$$

If the external characteristic is flat (the total pressure drop $\Delta P = \Delta P_1 = \Delta P_2 = \ldots = \Delta P_n$ = const and $H_{loop} = 0$), thus the channels are independent of each other and the characteristic equation becomes

$$\prod_{i=1}^{N} H_i = 0. \qquad [9]$$

The authors have found, through experiment, that the total flow rate is constant for DWO with balanced heating and without a surge tank. So, the characteristic [7] or [8] is more suitable to the parallel channel system.

3.2. Stability evaluation

According to linear control theory, the stability of the system can be evaluated by the location of the zeros (roots) of the closed-loop characteristic polynomial. The system is asymptotically stable if and only if all the roots of the characteristic polynomial lie on the left-hand side of the s-plane (Roshenbrock 1974; Ogata 1970).

In the frequency domain, the Nyquist stability criterion is convenient to use and has more advantages as it gives not only the relevant stability information but also the margins. If N_{po} is the number of poles of the open-loop transfer matrix on the right-hand side of the s-plane, $N_{\mathbf{R}}$ is the number of clockwise circles of $\det \mathbf{R}(j\omega)$ around the origin and Z is the number of roots of the close-loop characteristic polynomial on the right-hand side of the s-plane, then the sufficient and necessary asymptotic stability of the closed-loop system is

$$N_{\mathbf{R}} + N_{po} \equiv Z = 0. \qquad [10]$$

If $N_{po} = 0$, then the stability condition of the DWO in parallel boiling channels is

$$N_{\mathbf{R}} = 0. \qquad [11]$$

$N_{\mathbf{R}}$ can be obtained from the track of $\det \mathbf{R}(j\omega)$ when $\omega = 0 \to \infty$.

3.3. Fundamental oscillation modes

For two parallel channels, from [5] we obtain

$$H_1 H_2 + H_{\text{loop}}(H_1 + H_2) = 0, \qquad [12]$$

which can be resolved into

$$(H_C - H_{\text{loop}})(H_C + H_{\text{loop}}) = 0, \qquad [13]$$

where

$$H_C = [(H_1 + H_{\text{loop}})(H_2 + H_{\text{loop}})]^{1/2}.$$

Thus,

$$H_C - H_{\text{loop}} = 0, \quad H_C + H_{\text{loop}} = 0. \qquad [14]$$

When sustained oscillation takes place, from figure 9, the following can be obtained:

$$[\mathbf{I} + \mathbf{H}_{\text{test}}^{-1}\mathbf{H}_{\text{loop}}]\delta \mathbf{W}_{\text{in}} = 0. \qquad [15]$$

Hence

$$\frac{\delta W_1}{\delta W_2} = \pm\left(\frac{H_1 + H_{\text{loop}}}{H_2 + H_{\text{loop}}}\right)^{1/2}. \qquad [16]$$

If $H_1 = H_2$, then

$$\delta W_2 = \pm \delta W_1, \qquad [17]$$

which correspond to in-phase and out-of-phase oscillations, respectively.

The authors have found, through experiment, that under the condition of balanced (equal) heating between two channels, there exists only out-of-phase oscillation, with the total flow rate being constant.

3.4. Physical model

The governing conservation equations based on the drift-flux model, together with other constitutive equations (including heater wall dynamics, flow friction and heat transfer correlations and lateral turbulent mixing) are integrated along the channel length which is divided into K subsections on which the variables and relative parameters are treated as unchanged and have their value at the node. Thus, a set of multinode (non-linear) ordinary differential equations replace the original non-linear partial differential equations (Xiao *et al.* 1990).

In order to evaluate the stability of the parallel boiling channel system in the frequency domain, the above nodal equations are perturbed, linearized and Laplace-transformed near the system's steady-state operating parameters.

In any one subsection, the set of resulting nodal equations can be written in matrix form as

$$\mathbf{A}_k\,\delta\tilde{\mathbf{Y}}_k + \mathbf{B}_k\,\delta\tilde{\mathbf{Y}}_{k+1} = \delta\tilde{\mathbf{Z}}_k,\quad k = 1, K, \qquad [18]$$

where

$$\delta\tilde{\mathbf{Y}}_k = [\delta\tilde{\mathbf{G}}^k, \delta\tilde{\mathbf{H}}^k, \delta\tilde{\mathbf{P}}^k]^{\mathrm{T}},$$

$$\delta\tilde{\mathbf{G}}^k = [\delta\tilde{G}_1^k, \delta\tilde{G}_2^k, \ldots, \delta\tilde{G}_N^k]^{\mathrm{T}},$$

$$\delta\tilde{\mathbf{H}}^k = [\delta\tilde{h}_1^k, \delta\tilde{h}_2^k, \ldots, \delta\tilde{h}_N^k]^{\mathrm{T}},$$

$$\delta\tilde{\mathbf{P}}^k = [\delta\tilde{P}_1^k, \delta\tilde{P}_2^k, \ldots, \delta\tilde{P}_N^k]^{\mathrm{T}}$$

$$\mathbf{A}_k = \begin{bmatrix} \underset{(N\times N)}{\mathbf{A}_1^{k,1}} & \underset{(N\times N)}{\mathbf{A}_2^{k,1}} & \underset{(N\times N)}{\mathbf{A}_3^{k,1}} \\ \underset{(N\times N)}{\mathbf{A}_1^{k,2}} & \underset{(N\times N)}{\mathbf{A}_2^{k,2}} & \underset{(N\times N)}{\mathbf{A}_3^{k,2}} \\ \underset{(N\times N)}{\mathbf{A}_1^{k,3}} & \underset{(N\times N)}{\mathbf{A}_2^{k,3}} & \underset{(N\times N)}{\mathbf{A}_3^{k,3}} \end{bmatrix}_{3N\times 3N}$$

and

$$\mathbf{B}_k = \begin{bmatrix} \underset{(N\times N)}{\mathbf{B}_1^{k,1}} & \underset{(N\times N)}{\mathbf{B}_2^{k,1}} & \underset{(N\times N)}{\mathbf{B}_3^{k,1}} \\ \underset{(N\times N)}{\mathbf{B}_1^{k,2}} & \underset{(N\times N)}{\mathbf{B}_2^{k,2}} & \underset{(N\times N)}{\mathbf{B}_3^{k,2}} \\ \underset{(N\times N)}{\mathbf{B}_1^{k,3}} & \underset{(N\times N)}{\mathbf{B}_2^{k,3}} & \underset{(N\times N)}{\mathbf{B}_3^{k,3}} \end{bmatrix}_{3N\times 3N};$$

$\delta\tilde{\mathbf{Z}}_k$ is a $3N \times 1$ column vector including the internal heat generation perturbation for all channels in the kth axial node.

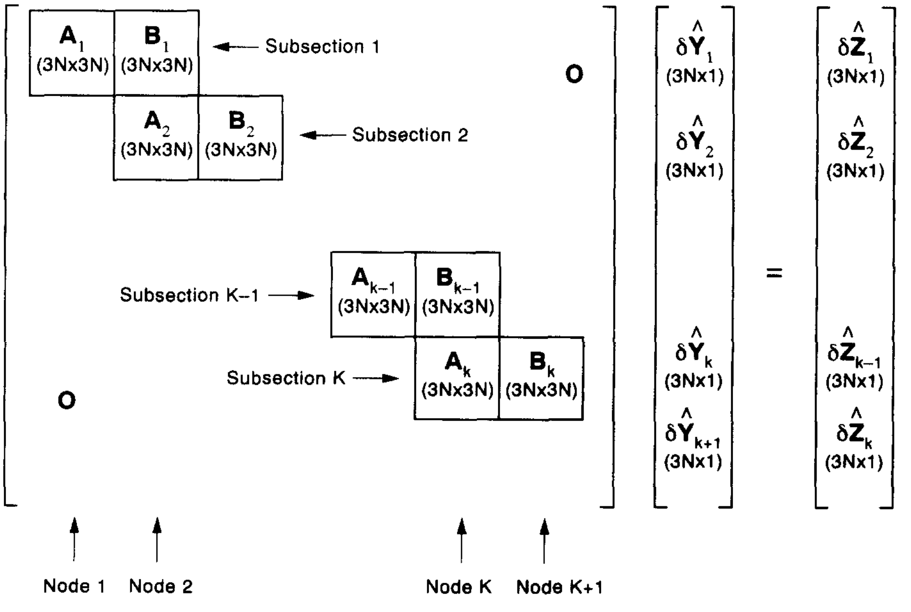

Figure 10. Matrix representation of the nodal equation of the multichannel system.

Equation [18] can be written for all subsections ($k = 1, 2, \ldots, K$) and cast into the block matrix shown in figure 10, from which we can find the recurrence relation to obtain

$$\delta \tilde{\mathbf{Y}}_{k+1} = \left[\prod_{k=1}^{K} (-\mathbf{B}_k^{-1}\mathbf{A}_k)\right]\delta \tilde{\mathbf{Y}}_1 + \sum_{k=1}^{K} \left\{\delta_{k,K}\mathbf{B}_k^{-1} + (1-\delta_{k,K})\left[\prod_{k'=k+1}^{K} (-\mathbf{B}_{k'}^{-1} \quad \mathbf{A}_{k'})\right]\mathbf{B}_k^{-1}\right\}\delta \tilde{\mathbf{Z}}_k. \quad [19]$$

Solving for its exit pressure perturbation, we obtain

$$\underset{N\times 1}{\delta \tilde{\mathbf{P}}_{\text{ex}}} = \underset{N\times N}{\mathbf{M}_{\text{G}}}\, \underset{N\times 1}{\delta \tilde{\mathbf{W}}_{\text{in}}} + \underset{N\times N}{\mathbf{M}_{\text{h}}}\, \underset{N\times 1}{\delta \tilde{\mathbf{H}}_{\text{in}}} + \underset{N\times N}{\mathbf{M}_{\text{P}}}\, \underset{N\times 1}{\delta \tilde{\mathbf{P}}_{\text{in}}} + \sum \underset{N\times 8N}{\mathbf{M}_{\text{s}}}\, \underset{8N\times 1}{\delta(\tilde{\mathbf{Q}}_{\text{W}})_i^k}. \quad [20]$$

For the special case when $H_{\text{in}} = \text{const}$ and $(Q''_{\text{W}})_i^k = \text{const}$, we obtain from [20]:

$$\delta(\Delta P_i) = H_i(s)\delta W_{\text{in}}, \quad [21]$$

where $H_i(s)$ is an individual channel transfer function, which constitutes the transfer matrix H_{test} in figure 9 and the closed-loop characteristic [6] or [7].

The stability of the system, can then be estimated by the location of the roots of the characteristic equation, or by the Nyquist stability criterion.

A computer program, named DENSITY-PARA, is coded for the stability analysis of a parallel boiling channel system with or without cross-connection. Using this model, the effect of the main parameters on the system stability can be analyzed, including the coupling effect between channels and between channels and the external loop, the effect of unequal inlet throttling and unequal wall heating between channels, etc.

3.5. Calculation results

The authors performed the calculation for the DWO in two parallel boiling channels without cross-connection in some parameter ranges. In the calculation, the basic assumption was that the total flow rate $W_t = \text{const}$, which was proved by the DWO experiment. In other words, the external loop characteristic curve is stiff, or $H_{\text{loop}} = \infty$. The DWO calculated is the channel-to-channel instability. Thus, the characteristic equation [7] or [8] was used for the stability calculation.

In order to show the results more clearly and informatively, the authors used several parameter coordinates for the DWO boundary. The following coordinates have been used and compared:

$$q''_{\text{w}} \sim G, \quad q''_{\text{w}} \sim P, \quad q''_{\text{w}} \sim \Delta T_{\text{sub}}, \quad [22]$$

$$X_{\text{e}} \sim G, \quad X_{\text{e}} \sim P, \quad X_{\text{e}} \sim \Delta T_{\text{sub}}, \quad [23]$$

$$\frac{C_{pf}\Delta T_{\text{sub}}}{H_{\text{fG}}} \sim \frac{q''_{\text{w}}}{WH_{\text{fG}}}, \quad [24]$$

$$N_{\text{pch}} \sim N_{\text{sub}}, \quad [25]$$

and

$$N_{\text{pch}} \sim \Delta T_{\text{sub}}, \quad [26]$$

where N_{pch} and N_{sub} are called the phase-change number and subcooling number, respectively, and are defined as

$$N_{\text{pch}} \equiv \frac{P_h L q''_{\text{w}}}{WH_{\text{fG}}} \cdot \frac{\rho_{\text{L}} - \rho_{\text{G}}}{\rho_{\text{G}}}, \quad N_{\text{sub}} \equiv \frac{C_{\text{pf}}\Delta T_{\text{sub}}}{H_{\text{fG}}} \cdot \frac{\rho_{\text{L}} - \rho_{\text{G}}}{\rho_{\text{G}}}. \quad [27]$$

The coordinates in [22] can directly reflect the effects of the parameters concerned, but other information is limited. The coordinates in [24] can correlate all the DWO boundary data almost on one line for all the parameters in a certain system, but the higher pressure data lie on the upper-right part of the line, while the lower pressure data lie on the lower-left part of the line, due to the fluid property changing with pressure. The coordinates in [25] are a little better than those in [24]. They can also correlate all the DWO boundary data almost on one line for all the parameters in a certain system, but the pressure has the opposite effect to that in coordinates [24], also due to the fluid property changing with pressure. The coordinates in [26] prove to be more informative and better.

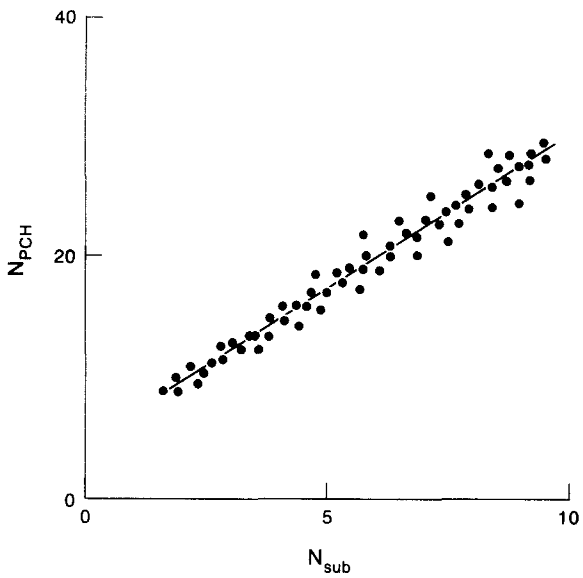

Figure 11. DWO boundary on the $N_{pch} \sim N_{sub}$ curve.

Figure 11 gives some calculational results for two parallel boiling channels with equal heating in $N_{pch} \sim N_{sub}$ coordinates. Some results in $N_{pch} \sim \Delta T_{sub}$ coordinates are shown in figure 7. The calculational results are in good agreement with the experimental data.

4. CONCLUSION

(1) The DWO in parallel boiling channels can exist under pressures up to, at least, 192 bar, while no DWO was observed over 207 bar.

(2) In a parallel boiling channel with balanced heating, the DWO takes the form of channel-to-channel oscillation. The magnitude of the DWO in an individual channel can be several times larger than that of the total flow rate, which can remain almost constant. So we cannot judge the start or existence of the DWO in parallel boiling channels by the total flow rate oscillation alone.

(3) The DWO in parallel boiling channels takes place more easily than in a single channel. Parallel boiling channels with unbalanced heating are more stable than those with balanced heating.

(4) The DWO in parallel boiling channels can occur before the start of the PDO in some conditions. The PDO can take place without an upstream surge tank.

(5) The 2nd DWO was first found in high-pressure parallel boiling channel systems. It can occur under pressures up to 100 bar. It is regular and periodical and takes place in the positive portion of the ΔP–G curve with an exit steam quality <0.1.

(6) The calculational results by the program DENSITY-PARA, based on the multiinput, multioutput transfer matrix method and the drift-flux model, were compared with the experimental results, and the agreement was good.

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