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Review on two-phase flow instabilities in narrow spaces

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Abstract

Instabilities in two-phase flow have been studied since the 1950s. These phenomena may appear in power generation and heat transfer systems where two-phase flow is involved. Because of thermal management in small size systems, micro-fluidics plays an important role. Typical processes must be considered when the channel hydraulic diameter becomes very small.

In this paper, a brief review of two-phase flow instabilities encountered in channels having hydraulic diameters greater than 10 mm are presented. The main instability types are discussed according to the existing experimental results and models.

The second part of the paper examines two-phase flow instabilities in narrow spaces. Pool and flow boiling cases are considered. Experiments as well as theoretical models existing in the literature are examined. It was found that several experimental works evidenced these instabilities meanwhile only limited theoretical developments exist in the literature.

In the last part of the paper an interpretation of the two-phase flow instabilities linked to narrow spaces are presented. This approach is based on characteristic time scales of the two-phase flow and bubble growth in the capillaries.

Keywords: Two-phase flow; Boiling; Instabilities; Vapour recoil; Confined space; Small channel

1. Introduction

The boiling process plays a key role in several applications. Boilers, evaporators, cooling systems are widely used in industries. This process is used to enhance heat transfer in many thermal components and energy systems. The optimum design of these equipments requires good knowledge of the involved phenomena and suitable tools. Two-phase flow instabilities may take place when boiling occurs in the loops. These undesired effects must be well known and predicted because it can induce mechanical vibrations in the system, degrade the heat transfer performances, etc.

Two-phase flow instability is a complex topic because several effects may occur simultaneously and play a role in a coupled way. To analyse the phenomena involved in such situations, a huge number of parameters might be taken into account. The research in this field took off in the 1950s and because of the development of high-density boilers several studies were performed until the 1980s. Experiments, theories and numerical codes were carried out in this period. Two-phase flow instabilities were introduced in the literature by Ledinegg (1938). These research works allowed a better understanding of the phenomena involved in the two-phase flow instabilities. One of the first reviews on two-flow instabilities was made by Bouré et al. (1973). These authors classified the various types and analysed the different mechanisms of two-phase flow instabilities. Several reviews on the two-phase flow instabilities have been made by Bergles (1976), Ishii (1976) and Yadigaroglu (1981). They presented the several phenomena and theories available in the literature.

Developments of small systems with thermal management have appeared during the last two-decades. In some of them the evaporation and boiling are involved because it allows several advantages such as heat transfer enhancement, constant temperature. For large thermal management systems, two-phase flow instabilities may also occur. Several

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authors dealing with boiling or phase change phenomena in narrow spaces and thermal components (compact heat exchangers, loop heat pipes) have observed such behaviours. What is more interesting, when compared to large systems, is the often appearance of the instabilities as the hydraulic diameter decreases and the applied heat flux increases. Kandlikar (2003) and Bergles et al. (2003) gave some of the first interpretations of the two-phase flow instabilities in narrow channels. They also used the classical theories developed for large hydraulic diameters to interpret the instabilities observed in small hydraulic diameter channels.

When boiling occurs similar phenomena might be found whatever the hydraulic diameter size. In fact, when dealing with phase change phenomena the basic mechanisms such as nucleation, coalescence, fragmentation, and interfacial instabilities exist. Nevertheless, when decreasing the hydraulic diameter, some differences may exist. In a narrow channel the vapour growth phase is limited in the radial direction because of the small thickness. Only the large direction allows vapour growth when boiling occurs. As a result there can be some differences observed in the physical processes when compared to large hydraulic diameter systems. Small hydraulic diameters reduce the 3D effects of flow structures. Thus only the main processes on the development of the two-phase flow instabilities will remain.

The first part of this paper is devoted to a presentation of the main instabilities encountered in two-phase flow systems for large hydraulic diameter. A brief review of the mechanisms will be discussed. In the second part we will focus on the particular case of the instabilities encountered in narrow spaces. Gravitational as well as forced flow in small ducts will be considered. A survey of the existing results in the literature will be presented. In the third part the possible mechanisms of two-phase flow instabilities will be discussed. An analysis of a specific dry out leading to the typical instability found in narrow spaces will be given.

2. Two-phase flow instabilities

When two fluids are in contact through an interface, instabilities may appear because of physical effects present (inertia, capillary, shear). Two-phase flow instabilities are more complicated because several interfaces are involved and because they occur under flow conditions.

A two-phase flow is considered stable when, for any applied disturbance, the new operating conditions tend to the initial one. The two-phase flow becomes unstable when for any disturbance a jump from one state to another is observed. Ledinegg (1938) investigated for the first time these instabilities. He studied in particular flow-excursion instability. This may occur when the pressure drop-flow rate characteristic exhibits an *N*-shape and a typical external pressure difference flow rate characteristic (Fig. 1).

When considering a simple system comprising a pump, and a heated channel where flow boiling occurs, the hydraulic system is characterised by its pressure difference $p_3 - p_1$:

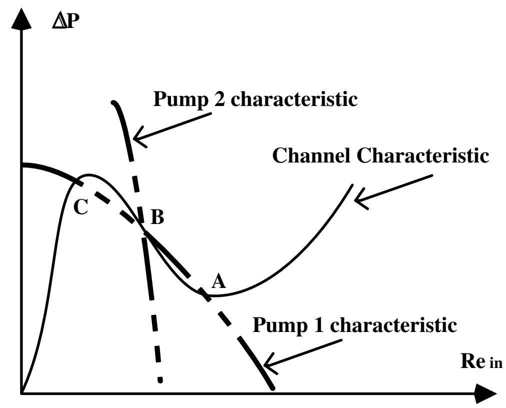

Fig. 1. Two-phase pressure drop characteristic of the pump and a channel versus the inlet liquid Reynolds number.

$$p_3 - p_1 = \Delta p_{\mathrm{p}} - \Delta p_{\mathrm{c}} - I\frac{\mathrm{d}\dot{m}}{\mathrm{d}t} \qquad (1)$$

where p_1 and p_3 are the instantaneous inlet and outlet pressure, respectively, Δp_{p} and Δp_{c} are the steady state pressure drop in the pump and channel sections respectively, I the system inertia (pump and channel), $\dot{m}$ the mass flow rate and t the time.

If we suppose small perturbations of this equilibrium state, the following flow rate perturbation equation is deduced:

$$I\frac{\mathrm{d}\delta\dot{m}}{\mathrm{d}t} = A\delta\dot{m} \qquad (2)$$

where A is the amplification rate given by the following relation:

$$A = \frac{\partial(\Delta p_{\mathrm{p}})}{\partial\dot{m}} - \frac{\partial(\Delta p_{\mathrm{c}})}{\partial\dot{m}} \qquad (3)$$

From the relationship seen in Eq. (3), it is easy to conclude that the system is unstable when the slope of the two-phase flow characteristic, in the decreasing part of the curve, is higher than that for the pump (pump 1 characteristic). On the contrary (pump 2 characteristic), the flow-excursion instability cannot occur (see Fig. 1). Points A and C are stable operating conditions for any flow rate fluctuation. In fact when increasing the flow rate, the system delivery cannot supply the required pressure drop in the channel. The fluid decelerates to its initial flow rate value. When decreasing the flow rate at points A and C the pressure drop supply is higher than the required one, the fluid accelerates and returns to its initial state. At point B, a flow rate fluctuation leads to operating conditions either A or C, depending on whether the flow rate is increased or decreased.

Since these first works of Ledinegg (1938), several two-phase flow instabilities were evidenced and studied. They were classified into two groups: static and dynamic two-phase flow instabilities.

The static two-phase flow instabilities are characterised by a change from a steady state condition to another condition. Flow excursion, Boiling crisis, and flow pattern transition belong to this group. The mechanisms and the characteristics are somewhat well identified. These instabilities could be checked using the steady state relations.

The second group concerns dynamic two-phase flow instabilities. Several types were classified in this group. Density wave oscillations are the most common instabilities encountered in two-phase flow systems. These instabilities result from the feedback between the flow rate; the vapour generation rate and the pressure drop in a boiling channel. In fact when flow boiling in a heated channel takes place, a decreasing flowrate induces a rise of the enthalpy rate and consequently the fluid density. This variation affects the heat transfer and the channel pressure drop. According to the operating and boundary conditions, finite propagation time induces phase-angle shifts between the channel pressure drop and the inlet flow leading to self-sustained oscillations. These instabilities have been extensively studied in 1970s. The influence of geometrical and boundary conditions were investigated by several authors (Bouré et al., 1973; Bergles, 1976; Ishii, 1976; Yadigaroglu, 1981). The characteristic periods of the oscillations are closely related to the residence time of the fluid in the channel and the frequencies are low (∼1 Hz).

Thurston et al. (1966) and Bergles et al. (1967), evidenced acoustic oscillations. These oscillations were observed in specific conditions such as film boiling, subcooled boiling, and cryogenic systems. This instability is triggered by the amplitude film thickness variation, bubble collapse, which in turn induces a change in pressure. The amplitude of the acoustic oscillations is generally small with frequencies varying in the range 10–100 Hz. From the practical application point of view, acoustic instabilities are considered with less importance. Nevertheless high amplitudes have been observed by Bergles et al. (1967).

Density wave and acoustic oscillations are classified as "pure" dynamic instabilities. Thermal oscillations, pressure drop oscillations and parallel channel instabilities are compound dynamic instabilities. In fact the latter result from interactions between two or more effects.

For example, pressure drop oscillations are due to the interaction between the channel and the compressible volume. These oscillations are nevertheless triggered by flow excursion and the frequencies are very low (<0.1 Hz).

Mathematical models were developed to describe the dynamic instabilities. Analytical models and computer codes were proposed in the literature to predict one or more of these dynamic instabilities according to the assumptions used. Several of these tools were successfully applied to experimental cases and the measured frequencies were qualitatively well predicted.

Stability maps were proposed in dimensionless parameters by authors such as Bouré (1966), Ishii and Zuber (1970) and Yadigaroglu and Bergles (1972). The proposed dimensionless parameters differ according to the authors. For example Ishii and Zuber (1970) used a stability map based on the subcooling and phase change numbers respectively defined as

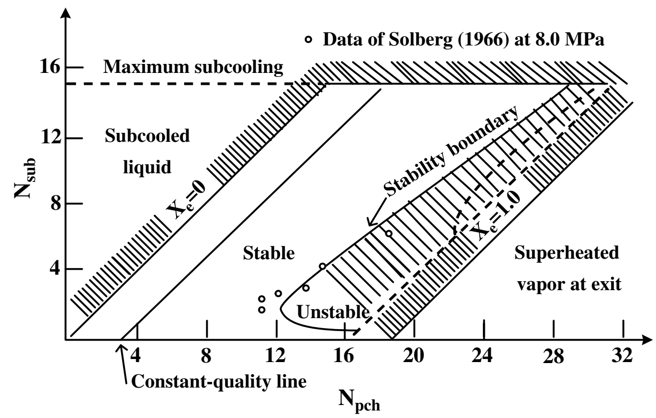

Fig. 2. Stability map in non-dimensional numbers proposed by Ishii and Zuber (1970).

$$N_{sub} = \frac{\Delta h_{in}}{h_{lg}} \frac{\Delta \rho}{\rho_g}; \quad N_{pch} = \frac{qL}{u_{in} h_{lg}} \frac{\Delta \rho}{\rho_g \rho_l} \tag{4}$$

where Δh_{in} is the subcooling, $\Delta\rho$ liquid–gas density difference, ρ_g, ρ_l gas and liquid densities, h_{lg} latent heat of vaporisation, q power density and L the heated channel length.

Fig. 2 shows a stability map established by Ishii and Zuber (1970). On this map stable and unstable regions are shown. Although there is no universal stability map, this representation is useful for understanding the influence of the parameters on the system stability.

This brief review shows that several investigations in two-phase flow instabilities have been carried out essentially for systems having large hydraulic diameters. The research and developments have given a better understanding of the phenomena and have helped the designers to avoid the undesired effects of these instabilities.

3. Two-phase flow instabilities in narrow spaces

3.1. Instabilities in pool boiling case

Pool boiling in narrow spaces is encountered in a volume where, at least, one space direction is small enough to modify the characteristics of the classical pool boiling. This particular situation is found in cooling electronic systems, automotive engines, industrial compact heat exchangers, etc.

Katto and Yokoya (1966) investigated for the first time water boiling between two parallel plates. They evidenced modifications of the boiling curve when the plates are separated by a distance less than 1 mm. For greater distances the boiling curve remains unchanged. Several authors studied the mechanisms of boiling in narrow channels (Yao and Chang, 1983; Bar-Cohen and Schweitzer, 1986; Xia et al., 1992). For low heat fluxes they found a heat transfer enhancement as the confinement effect is increased. For high heat fluxes they observed a degradation of the heat transfer as the confinement increases. Bonjour and Lallemand (1998) investigated flow patterns. They evidenced

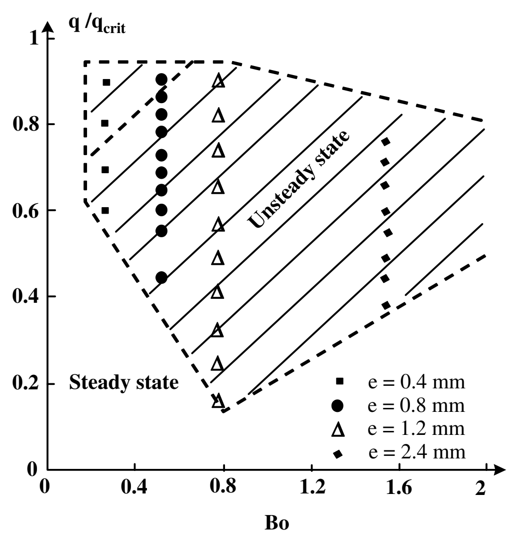

Fig. 3. Stability map in non-dimensional parameters ((q/q_{crit})–Bond number (Bo)) of pool boiling in narrow channel (Aït Ameur et al., 2004).

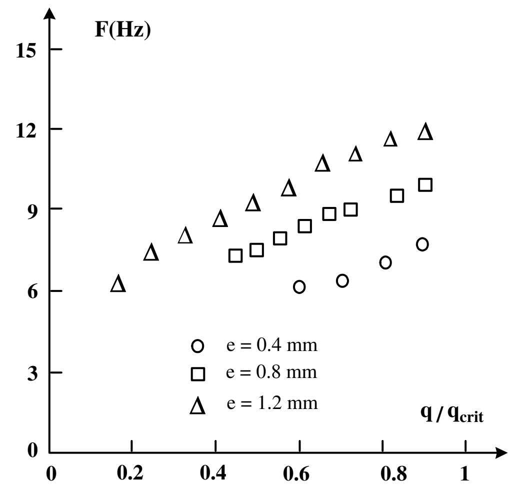

Fig. 4. Oscillation frequency versus non-dimensional heat flux for several channel thickness (Aït Ameur et al., 2004).

three different flow patterns depending on the confinement: isolated bubbles or partial nucleate fully developed nucleate boiling with bubble coalescence and the transition to critical heat flux with the appearance of partial dry out.

Temperature measurements were carried out by Aoki et al. (1982). These authors measured temperature fluctuations for water boiling in channels of less than 1 mm thick. The temperature amplitudes were about 1 K with frequencies varying from 1 to 2 Hz. Fujita et al. (1987) studied the boiling instabilities in narrow channels. They analysed the evolution of the dry out and rewetting times in vertical channels with several thicknesses ($150\ \mu m < e < 5000\ \mu m$). The oscillations were found to vary with the imposed heat flux.

Recent investigations made by Aït Ameur et al. (2004) evidence two-phase flow instabilities. These authors performed experiments with a copper heated block immerged in *n*-pentane. A parallel plate is placed in front of the heated surface. Thus a narrow channel is created. The gap between the plates varies from 200 µm to 2400 µm. These authors determined the characteristic frequencies of the two-phase oscillations for several operating conditions (heat flux q, channel thickness e). The frequencies were found to vary in the range 5–10 Hz (Fig. 4). When reducing the channel hydraulic diameter the frequency oscillation decreases, while it increases with the heat flux (Aït Ameur et al., 2004). Systematic investigations were carried out. The authors proposed a stability map drawn in the non-dimensional heat flux (q/q_{crit})–Bond number (Bo) (Fig. 3).

3.2. Instabilities in flow boiling case

Thermal management of small systems motivated several authors to develop R&D on manufacturing of these systems and to investigate the thermo-hydraulic performances in small channels (flow distribution, heat transfer, etc.). Because of the hydraulic diameter decreasing, conjugate heat transfer effects associated to axial variations become dominant for these small sizes. Among the various aspects encountered in small channels, two-phase flow heat transfer, flow pattern and pressure drop have been extensively investigated in the last decade (Fukano and Kariyasaki, 1993; Triplett et al., 1999; Peng et al., 1998; Thome et al., 2004; Dupont et al., 2004).

Several authors evidenced "instabilities" in single and parallel micro-channels (Kennedy et al., 2000; Kandlikar et al., 2001; Kandlikar, 2002; Hetsroni et al., 2003; Qu and Mudawar, 2003).

Hetsroni et al. (2003) performed experiments with water flowing in parallel micro-channels. They evidenced quasi-periodical rewetting and refilling of the micro-channels at high heat fluxes. Kandlikar (2002) noted large amplitude fluctuations in multi-channel evaporators. Flow pattern observations revealed a flow reversal in some channels with expanding bubbles pushing the liquid–vapor interface in both upstream and downstream directions (Kandlikar et al., 2001).

Qu and Mudawar (2003) found two behaviours of fluctuations in a set of parallel channels: The first, where the oscillations in the channels are in phase and the second, where the oscillations behave in a chaotic way.

Two-phase flow instabilities were also reported in single channels (Yan and Kenning, 1998; Kenning and Yan, 2001; Brutin et al., 2003). These authors measured wall temperature fluctuations r pressure fluctuations. Kennedy et al. (2000) determined the onset of the instabilities by using the pressure drop signal.

Brutin et al. (2003) carried out experiments in a single channel with *n*-pentane as the working fluid. These authors derived from the experiments a stability map drawn in non-dimensional parameters: outlet vapour quality (χ_{out})–inlet Reynolds number (Re_{in}). The critical curve is found to vary linearly: $\chi_{out} = ARe_{in}$ (Fig. 5). The slope is found to depend with the channel inlet conditions. A two-phase pressure drop characteristic was carried out for several heat fluxes

(Brutin and Tadrist, 2004). The unstable regime was found in the first zone of the N-shape curve (Fig. 6). The amplitude fluctuations become higher as the inlet Reynolds number becomes smaller.

4. Phenomena description

4.1. Confinement number

Two-phase flow instabilities are often encountered. In big channels and large systems, these instabilities could be due to several mechanisms as it has been presented in Section 2. In what follows we will examine the possible mechanisms playing a role in the instabilities in small channels, according to the experimental results and the observations reported in the literature.

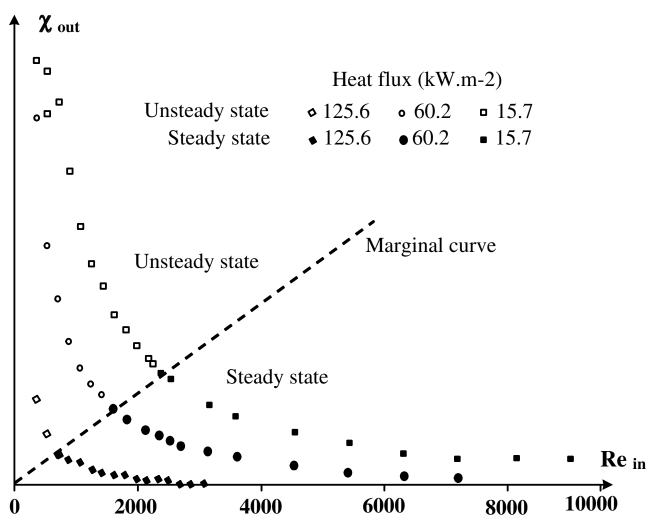

Fig. 5. Outlet vapor quality versus the inlet Reynolds number. The dashed line is the marginal stability curve (Brutin and Tadrist, 2004).

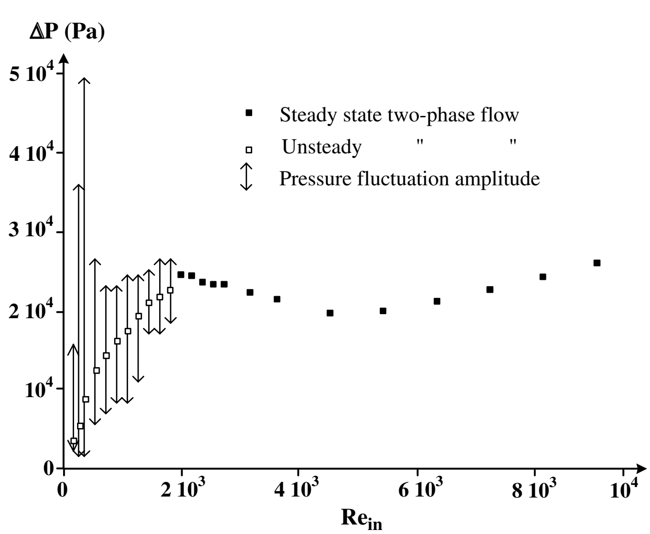

Fig. 6. Pressure drop characteristic for a narrow channel. Oscillations are evidenced in the first part of the N-shape curve (Brutin and Tadrist, 2004).

Although we are dealing with boiling in narrow channels, the two-phase flow instabilities mechanisms observed in large channels may also occur in small channels. Nevertheless because of the small thicknesses some differences with larger channels may exist. In fact, in narrow channels the wall effects may play a dominant role while in larger channels phenomena occurring in the fluid bulk also play an important role. In particular the 3D effects existing in large channels are substantially reduced in narrow channels.

To define a limit between small and large hydraulic diameters a characteristic length according to the phenomena occurring in the channel is introduced. For our purpose we have to make a distinction between the channel sizes in relation to the boiling occurring in the channel. In this latter case one important characteristic length, is the capillary length $l_c = \left(\frac{\sigma}{g\Delta\rho}\right)^{\frac{1}{2}}$ which is directly linked to the bubble detaching from the channel wall. This characteristic length differs according to the thermo-physical properties of the fluid. When comparing this capillary length to the hydraulic diameter, different behaviours may be observed. The confinement number defined as the ratio of the capillary length to channel diameter $Co = \frac{l_c}{d}$ is useful for analysing the two-phase flow channels (Kew and Corwell, 1996).

For $Co < 1$, boiling is considered to occur in large hydraulic diameter channels. For $Co > 1$, the capillary effects play an important role for two-phase flow. In this case, the growing bubbles may invade the channel cross section before it detaches from the wall. The bubbly regime in this case could not be fully developed. In addition the coalescence effects may be enhanced. Thus elongated bubble regime may appear at an early stage of the boiling process in narrow channels. The bubbly regime appears at the onset of boiling in short channel lengths while it is fully developed in larger channels.

4.2. Observed instabilities in narrow channels

According to the two-phase flow instabilities classification proposed for large channels, the static two-phase flow instabilities may appear for narrow channels ($Co > 1$). Flow excursion, flow-regime transition and boiling crisis may also occur for small channels. No restrictions could appear because of the small channel sizes. To predict the onset of these instabilities it is necessary to derive the suitable relations of friction factor, heat transfer correlation and flow regime map. For small channels ($Co > 1$) two-phase flow regime and heat transfer laws are not well predicted. Investigations are still needed for the steady state case.

For parallel channels investigations, the frequencies reported by Hetsroni et al. (2003), were around 0.5 Hz. They are characterised by various modes of flow redistribution. As for large hydraulic diameters the instability results from the interaction mechanism between the channels.

Two-phase flow instabilities reported in the literature for flow boiling and pool boiling conditions in single narrow spaces exhibit oscillations with frequency values ranging from 1 to 10 Hz.

The two-phase flow oscillations evidenced in single and parallel narrow channels correspond to dynamic instabilities with respect to the classification proposed for large hydraulic diameter (Bouré et al., 1973). The frequency oscillations were measured in the range 1–10 Hz.

According to the characteristic of the oscillations and the descriptions given by the authors, it seems that the dynamic instabilities observed in narrow channels might be density wave oscillations, pressure drop or thermal oscillations. This classification is of course not enough to characterise the instabilities observed in narrow channels. A better understanding of the phenomena is needed. For this it is necessary to have a more detailed description of the mechanisms occurring in such systems.

Let us use the existing detailed description made by some authors in pool (Aït Ameur et al., 2004) and flow boiling cases (Brutin and Tadrist, 2004; Brutin, 2003).

4.2.1. Pool boiling case

Flow visualisations were made with a high speed camera by Aït Ameur et al. (2004). These authors have shown the different stages when the oscillations occur in the narrow channel. Hereafter are briefly reported their observations. Starting from a channel entirely filled with vapour, liquid enters in the channel from the bottom. As far as the liquid invades the channel, vapour bubbles are created on the wall. At first these remain attached due to the capillary viscous forces. Because of the liquid–vapour phase change an overpressure is induced leading to a vapour recoil. The recoil forces push the liquid–vapour mixture outside the narrow volume. When the vapour invades the channel volume, the vapour recoil as well as the overpressure are cancelled. The liquid again enters the heated channel and a new period starts.

4.2.2. Flow boiling case

Two-phase flow oscillations were also observed in a single narrow channel for flow boiling as mentioned in Section 3. In this case, a volumetric pump delivers a constant flow rate and a compressible tank is inserted between the heated channel and the volumetric pump. We describe hereafter the reported observations made by Brutin and Tadrist (2004) when instabilities occur. As far as the channel is fully filled by vapour, at a given position in the channel the instantaneous pressure reaches its minimum value. The liquid invades the channel from the inlet side meanwhile vapour bubbles are created on the heated wall. When the vapour production rate is high enough, an overpressure is induced leading again to a vapour recoil. The recoil forces push the two-phase mixture to the channel exit and inlet. The channel is again filled with vapour, with a pressure decrease. A new period starts again.

Experiments were carried out in the case where the compressible tank inserted between the pump and the channel is suppressed. Oscillations with less amplitudes were also evidenced (Brutin, 2003).

Flow reversal was observed to occur during narrow channel flow boiling by Jones and Judd (2003). The authors examined two-phase flow instability models involving the boiling crisis. Experimental data were compared with the existing correlations for the occurrence of the boiling crisis. The authors concluded that the instability was deemed to be caused by the onset of CHF and to be the result of dry out and rewetting of the heated surface.

When comparing pool and flow boiling instabilities the basic mechanisms leading to fluid oscillations seem to be similar. In fact Intermittent dry out is observed in narrow channels for pool and flow boiling conditions. Vapour production induces overpressures in the narrow channel and consequently, a vapour recoil in the possible directions of the channel can occur. As soon as the vapour production is reduced the vapour recoil forces are decreased. Because of the external forces (gravity, pump) the channel is again filled with liquid.

5. Phenomena analysis

To predict the instabilities evidenced in narrow channels, models are needed. Several types of models could be developed. Kandlikar (2003) proposed a first model to predict the critical heat flux in narrow channels. This model is based on the competition between the evaporation momentum force and the inertia force or the surface tension force. Thus two non-dimensional groups K_1 and K_2 were proposed:

$$K_1 = \left(\frac{q}{\dot{m}h_{\mathrm{lg}}}\right)^2 \frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}}; \quad K_2 = \left(\frac{q}{\dot{m}h_{\mathrm{lg}}}\right)^2 \frac{D}{\rho_{\mathrm{g}}\sigma} \tag{5}$$

where q is the heat flux, $\dot{m}$ mass flow rate, h_{lg} latent heat of vaporisation, ρ_{g}, ρ_{l} gas and liquid densities, σ surface tension, D departing bubble diameter.

A combination form of the non-dimensional groups $K_2K_1^{3/4}$ for representing the flow boiling critical heat flux were proposed (Kandlikar, 2003).

Brutin (2003) proposed a criterion for which the instability occurs. This criterion is based on the competition between the pressure difference induced by the vapour expansion and the pressure difference inducing the two-phase flow in the channel.

In what follows a simplified analysis is presented. It is based on the evaluation of the different characteristic times of the phenomena observed in the channel. To make this analysis we supposed that the oscillations are due to the competition of the vapour recoil force induced by the strong evaporation in the narrow channel and an external force. In the pool boiling case this force is induced by the gravity while it is induced by a pump in a forced flow case.

When the vapour is produced in the narrow channel, depending on the vapour rate an overpressure is induced. The vapour recoil pressure is expressed as

$$p_v - p_l = \dot{m}^2 \frac{\rho_l - \rho_v}{\rho_l \rho_v} \tag{6}$$

where $\dot{m}$ is the vapour mass flow rate produced by phase change, ρ_g, ρ_l gas and liquid densities.

Using the relation linking the vapour production rate and the heat flux $\dot{m} = k\frac{q}{h_{lg}}$, the previous equation might be written as

$$p_v - p_l = \left(k\frac{q}{h_{lg}}\right)^2 \frac{\rho_l - \rho_v}{\rho_l \rho_v} \tag{7}$$

k is a constant and h_{lg} the latent heat of vaporisation.

In the pool boiling case, if we assume that the external force drawing the liquid is the gravity force, the pressure difference governing the liquid flow in the channel is linked to the liquid height above the heated zone:

$$p_h - p_l \approx \rho_l g h \tag{8}$$

Assuming the vapour density negligible compared to the liquid one, the following equations might be derived from Eqs. (7) and (8):

$$R_{pb} = \left(k\frac{q}{h_{lg}}\right)^2 \frac{\rho_l - \rho_v}{\rho_l \rho_v} \frac{1}{\rho_l g h} \approx \left(k\frac{q}{h_{lg}}\right)^2 \frac{1}{\rho_v \rho_l g h} \tag{9}$$

In the flow boiling case, the external force is induced by the pump. The pressure difference governing the liquid flow is

$$R_{fb} = \left(\frac{q}{h_{lg} u_{in}}\right)^2 \frac{\rho_l - \rho_v}{\rho_l^2 \rho_v} \approx \left(\frac{q}{h_{lg} u_{in}}\right)^2 \frac{1}{\rho_l \rho_v} \tag{10}$$

R_{pb} compares the vapour recoil effects to the gravity effects while R_{fb} compares the vapour recoil to the inertia effects induced by the pump which pushes the liquid in the channel.

At the onset of the oscillations, the non-dimensional parameters have critical values. For pool boiling case (gravity force influence):

$$R_{pb}^c = \left(\frac{q^c}{h_{lg}}\right)^2 \frac{\rho_l - \rho_v}{\rho_l \rho_v} \frac{1}{\rho_l g h^c} \tag{11}$$

The corresponding critical curve is deduced from Eq. (12):

$$q^c = \left(R_{pb}^c g \frac{\rho_v \rho_l^2}{\rho_l - \rho_v}\right)^{1/2} h_{lg} h^{c^{1/2}} \tag{12}$$

As we can see the critical curve in a stability map (q, h), the marginal curve (q^c, h^c) is given by a power law: $q^c = A h^{c^{1/2}}$

For the flow boiling case, a similar procedure is applied. This leads, in the stability map (q^c, u_{in}^c), to the critical curve given by the following relation:

$$q^c = \left(R_{fb} \frac{\rho_l^2 \rho_v}{\rho_l - \rho_v}\right)^{1/2} h_{lg} u_{in}^c \tag{13}$$

Fig. 7 shows the variation of the critical heat flux versus the inlet fluid velocity in the case of n-pentane flowing in a small channel (Brutin and Tadrist, 2004). As we can see the critical heat flux q^c is a quadratic function of the critical inlet velocity u_{in}^c. The experimental law differs from the analytical model given by Eq. (13). This shows clearly the complex phenomenon occurring in a boiling channel when the instabilities appear.

5.1. Oscillations characteristic frequency

If the oscillations are due to CHF mechanism, the frequency might be evaluated from Hamamura and Katto (1983) model. This model allows the prediction of the time required for the rewetted heater surface to reach the CHF. The rewetting time must also be used for evaluating the period of the oscillations.

The other simplest model assumes that the oscillation period is a sum of two characteristic times: τ_v, τ_l. These are liquid draining due to vapour recoil and filling times respectively expressed as

$$\tau_l = \frac{l_c}{u_{in}}; \quad \tau_v = \frac{l_c}{v_i} \tag{14}$$

l_c is the characteristic length, u_{in} the inlet velocity, v_i liquid–vapour front velocity. The period of the oscillations is

$$\tau = \tau_l + \tau_v = l_c\left(\frac{1}{u_{in}} + \frac{1}{v_i}\right) \tag{15}$$

Replacing v_i by its expression the period time is

$$\tau = l_c\left(\frac{1}{u_{in}} + \frac{1}{\frac{\dot{m}}{\rho_l} - u_{in}}\right) \tag{16}$$

The oscillation frequency is deduced from the previous equation:

$$f = \frac{u_{in}}{l_c}\left(1 - \frac{\rho_l u_{in}}{\dot{m}}\right) \tag{17}$$

This relation is derived from a simplified model where several effects were neglected. The vapour recoil mechanisms must be the dominant mechanism among the others in narrow channel. This might be observed for a very low liquid inlet velocity and a high heat flux.

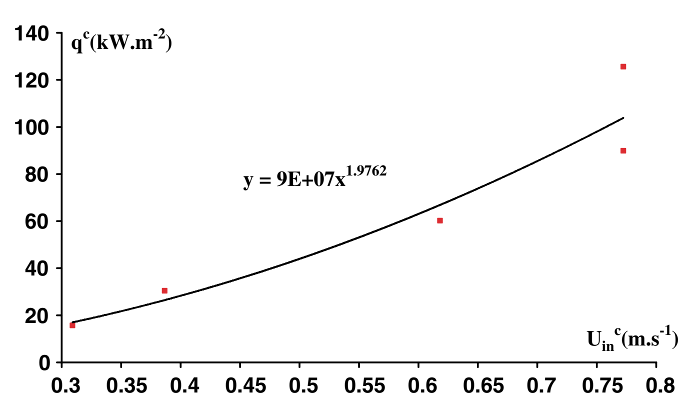

Fig. 7. Variation of the critical heat flux versus the critical inlet velocity for n-pentane boiling in a channel of 0.9 mm hydraulic diameter. This curve is deduced from the experimental results of Brutin and Tadrist (2004).

The previous relations give qualitative tendencies of the frequency and the critical curve.

To analyse the other possible mechanisms, such as density wave oscillations, models where variables are locally computed must be developed. This approach in relation with the experiments will help to better analyse the two-phase flow instabilities in narrow channels.

6. Conclusion

Two-phase flow instabilities are complex phenomena encountered whatever is the hydraulic diameter. These instabilities may have a harmful influence on the thermal systems. A brief review on two-phase flow instabilities has been made according to the classical approaches proposed in the 1960s. A review of two-phase flow instabilities in narrow spaces reveals that several investigations have been made recently and exist mainly from the experimental point of view.

At present, parallel channel oscillations and single channel oscillations were clearly identified in narrow channels. What is typical for these geometries is the appearance of an intermittent dry out which produces a vapour recoil in the mini-channel. Depending on the compressibility of the inlet zone of the channel, quasi-periodical pressure fluctuations are observed. These oscillations are due to the competition of the inertia or gravity effects and the vapour recoil pressure linked to the imposed heat flux on the wall.

Further experiments are needed in order to investigate other possible instability mechanisms. Local thermal and hydraulic measurements in conjunction with flow visualisation will be helpful. At this stage analytical and numerical models could be developed on the basis of the existing experiments. These approaches are required for predicting two-phase flow instabilities in narrow channels.

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