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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.
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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 $p_3 - p_1$:

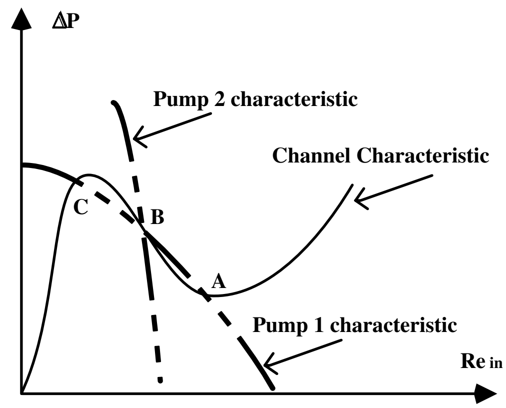

Fig. 1. Two-phase pressure drop characteristic of the pump and a channel versus the inlet liquid Reynolds number.

$$p_3 - p_1 = \Delta p_p - \Delta p_c - I\frac{d\dot{m}}{dt} \qquad (1)$$

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:

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

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

$$A = \frac{\partial(\Delta p_p)}{\partial\dot{m}} - \frac{\partial(\Delta p_c)}{\partial\dot{m}} \qquad (3)$$

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

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