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Inertia and compressibility effects on density waves and Ledinegg phenomena in two-phase flow systems

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HIGHLIGHTS

- The stability influence of piping fluid inertia on two-phase instabilities is studied.
- Inlet inertia stabilizes the system while outlet inertia destabilizes it.
- High-order modes oscillations are found and analyzed.
- The effect of compressible volumes in the system is studied.
- Inlet compressibility destabilizes the system while outlet comp. stabilizes it.

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ABSTRACT

The most common kind of static and dynamic two-phase flow instabilities namely Ledinegg and density wave oscillations are studied. A new model to study two-phase flow instabilities taking into account general parameters from real systems is proposed. The stability influence of external parameters such as the fluid inertia and the presence of compressible gases in the system is analyzed. High-order oscillation modes are found to be related with the fluid inertia of external piping. The occurrence of high-order modes in experimental works is analyzed with focus on the results presented in this work. Moreover, both inertia and compressibility are proven to have a high impact on the stability limits of the systems. The performed study is done by modeling the boiling channel using a one dimensional equilibrium model. An incompressible transient model describes the evolution of the flow and pressure in the non-heated regions and an ideal gas model is used to simulate the compressible volumes in the system. The use of wavelet decomposition analysis is proven to be an efficient tool in stability analysis of several frequencies oscillations.

1. Introduction

The occurrence of oscillations and instabilities may cause severe damages in many industrial systems, such as heat exchangers, nuclear reactors, re-boilers, steam generators, thermal-siphons, etc. These phenomena induced in boiling flows are of relevance for the design and operation of two-phase systems. Consequently the stability in thermal-hydraulic variables such as mass flux, pressure and temperature should be studied in detail to better understand and characterize the conditions for the occurrence of these phenomena. Several types of thermal-hydraulic instabilities can be found in two-phase flow systems as shown in Bouré et al. (1973).

Ledinegg instability, introduced by Ledinegg (1938), is considered the most common type of static instability. The occurrence of this instability is related to the slope of the pressure drop vs. flow characteristic curve of the system. Several works described the experimental occurrence of this phenomenon in several kinds of systems (see Padki et al., 1992; Zhang et al., 2009; Hamidouche et al., 2009).

The phenomenon called density wave oscillations (DWO), or thermally induced two-phase flow instability, is the most common type of dynamic instability occurring in real systems. There exist several experimental works describing the occurrence of this phenomenon (Ishii and Zuber, 1970; Yadigaroglu and Bergles, 1972; Saha et al., 1976; Yuncu, 1990; Wang et al., 1994; Ding et al., 1995). The main contradiction between those works is the description of high-order modes. While in Yadigaroglu's work (Yadigaroglu and Bergles, 1972) higher-order modes are experimentally observed, in Saha et al.'s (1976) investigation no higher modes are reported, even if special focus is made on searching for these modes. In addition, regarding the experimental study performed in the latter work, it is necessary to remark the fact that in Saha's experiment

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Nomenclature

Lowercase

h	specific enthalpy
f	Darcy friction factor
t	time coordinate
v	specific volume
x	themodynamic quality
z	space coordinate
ρ	density

Uppercase

A_{xs}	cross section area
D_H	hydraulic diameter
T	temperature
TP	two-phase
G	mass flux
K	valve constant
L	pipe length
P	pressure
P_H	wet perimeter
Q	constant heat source

Subscripts

HS	heated section
in	inlet
out	outlet
l, f	liquid
g	gas

the heated section is fixed in a by-pass configuration to assure a constant pressure drop condition (parallel channel condition). In this case all the pipes are 50 mm inside diameter and the heater is 10 mm inside diameter. Moreover, from the given information, the section before the heater (where the pre-heater, turbine flow-meter and flex-joint are situated) is at least 2 m long. It means that the inlet external inertia is higher than the inertia terms in the heated section. As it is shown later, the fluid inertia is playing an important role in the occurrence of high order modes. In the rest of the experimental works no focus is made regarding high-order modes. Actually by the data reported in Yuncu (1990), Wang et al. (1994), Ding et al. (1995) where the principal focus is given to pressure drop oscillations (slow oscillations), it is possible to see that the acquisition system was not able to sample fast enough to described these high-order phenomena.

Regarding the modeling and theoretical background of density waves oscillations, the investigations carried out in Ishii and Zuber (1970), Ishii (1971) constitute the theoretical basis in the understanding of density wave phenomenon. In these works a thermal equilibrium model is used to describe the system in a one-dimensional model. The Ishii–Zuber stability maps are also introduced in those works. In Saha et al. (1976), the use of a non-equilibrium model is proposed. For low sub-cooling this model seems to fit better to the experimental data. Nevertheless, in the high sub-cooling cases the equilibrium model fits better the experimental data. In Furutera (1986), the validity of the homogeneous model is discussed. In the latter work several pressure, sub-cooling and heat capacity models are compared with experimental data. It is proven that in general terms the best approximation is made with no sub-cooling model and heat capacity of the wall when that mechanism could be important (massive tubes). In Fukuda and Kobori (1979) a classification of the different types of density waves according to the most significant effects occurring in the system (inertia, gravity, friction) is presented. More recently, in Rizwan (1994b,a) a homogeneous equilibrium (no sub-cooling) model is used to study the phenomenon. Several aspects of the classical theoretical description of DWO are critically discussed. The introduction of non-uniform heating is discussed in Narayanan et al. (1997), Rizwan (1994a). The use of commercial codes and simplified lumped methods based on the homogeneous equilibrium models are described in Achard et al. (1985), Lahey and Podoski (1989), Ambrosini et al. (2000), Ambrosini (2007). Nevertheless, none of these theoretical works predict the occurrence of high-order modes in the sense of Yadigaroglu's work. In most of these works linearization techniques are used to analyze the stability of the systems. In addition, none of these works takes into account parameters of the external thermal-hydraulic loop as compressibility (gases) and external fluid inertia (piping). Just in some cases of vertical tubes a non-heated riser section is modeled but the main focus is given to the gravity and pressure drop influence.

The purpose of this work is to analyze the influence of the fluid inertia and compressibility volumes in different parts of the thermal-hydraulic loop. A new general model that includes those external parameters (inertia, compressibility, pump response) is introduced. A non-dimensional stability analysis of different cases is presented.

2. General model for instability analysis

In this section a new general model to study stability of two-phase flow systems is presented, as shown in Fig. 1. This model consists of: a constant pressure tank, P_{out}; a variable pressure tank in order to take into account the pump response and the pump evolution, $P_{in}(G_1, t)$; a heated section; two different surge tanks to simulate the effects of compressible volumes (non-condensable gas), V_{Si} and V_{So}; four incompressible pipe lines (inertia effects), L_i; and finally four localized pressure drops in each section, K_i. In this model the pressure difference between both tanks acts as the driving force and, according to the valves opening, the external characteristic (ΔP vs. G) results in a quadratic decreasing curve. The implemented model is based on the following assumptions,

- One-dimensional model.
- Two-phase homogeneous model.
- Thermodynamic equilibrium conditions.
- Colebrook pressure drop correlation in the single phase region and two-phase Müller-Steinhagen and Heck pressure drop correlation for two-phase flow region (Thome, 2006).

The mathematical description of the external system (surge tanks and piping) corresponds to the conservation of momentum, since an unheated incompressible model is assumed. For the case of the surge tanks an ideal isothermal gas model is assumed. The equations of the external system can be expressed as

$$\dot{P}_{si} = \frac{P_{si}^2}{P_{si0}V_{si0}} \frac{A_{xs}}{\rho_l}(G_2 - G_1) \tag{1}$$

$$\dot{P}_{so} = \frac{P_{so}^2}{P_{so0}V_{so0}} \frac{A_{xs}}{\rho_l}(G_4 - G_3) \tag{2}$$

$$\dot{G_1} = \left[P_{in}(G_1, t) - P_{si} - K_1 \frac{G_1|G_1|}{2\rho_l}\right] \frac{1}{L_1} \tag{3}$$

$$\dot{G_2} = \left[P_{si} - P_2 - (K_2 + 1) \frac{G_2|G_2|}{2\rho_l}\right] \frac{1}{L_2} \tag{4}$$

$$\dot{G_3} = \left[P_3 - P_{so} - (K_3 - 1) \frac{G_3|G_3|}{2\rho_{out}}\right] \frac{1}{L_3} \tag{5}$$

$$\dot{G_4} = \left[P_{so} - P_{out} - K_4 \frac{G_4|G_4|}{2\rho_{out}}\right] \frac{1}{L_4} \tag{6}$$