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Theoretical investigations on two-phase flow instability in parallel channels under axial non-uniform heating

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ABSTRACT

Two-phase flow instability in parallel channels heated by axial non-uniform heat flux has been theoretically studied in this paper. The system control equations of parallel channels were established based on the homogeneous flow model in two-phase region. Semi-implicit finite-difference scheme and staggered mesh method were used to discretize the equations, and the difference equations were solved by chasing method. Cosine, bottom-peaked and top-peaked heat fluxes were used to study the influence of non-uniform heating on two-phase flow instability of the parallel channels system. The marginal stability boundaries (MSB) of parallel channels and three-dimensional instability spaces (or instability reefs) under different heat flux conditions have been obtained. Compared with axial uniform heating, axial non-uniform heating will affect the system stability. Cosine and bottom-peaked heat fluxes can destabilize the system stability in high inlet subcooling region, while the opposite effect can be found in low inlet subcooling region. However, top-peaked heat flux can enhance the system stability in the whole region. In addition, for cosine heat flux, increasing the system pressure or inlet resistance coefficient can strengthen the system stability, and increasing the heating power will destabilize the system stability. The influence of inlet subcooling number on the system stability is multi-valued under cosine heat flux.

1. Introduction

The phenomenon of two-phase flow instability has been observed in many industrial domains like refrigeration systems, steam generators, boiling water reactors and reboilers. It has very adverse influences on thermal–hydraulic system, since the oscillations of the mass flow rate and system pressure induced by two-phase flow instability can cause structural vibrations of components, problems of system control, transient burn-out of the heat transfer surface and degradation of the heat transfer performance. It is obvious that the flow instabilities must be avoided and there should be an adequate margin to ensure the system stability. Flow instability plays an important role in water-cooled and water-moderated nuclear reactors. Therefore, predicting the thresholds of flow instabilities is an important work in the design and operation of nuclear reactors. In the past few decades, a considerable amount of numerical and experimental investigations on the two-phase flow instability have been carried out all over the world.

After the two-phase flow instability was introduced by Ledinegg (1938), plenty of subsequent researches (Boure et al., 1973; Lahey, 1980; Su et al., 2002; Papini et al., 2012) on the two-phase flow instability in heating channel system have been conducted. In recent years, the two-phase flow instability in parallel channels has attracted extensive attention since it is particularly difficult to be detected. In parallel channels system, an interaction between the channels can be established due to common boundary conditions. It is well known that the density wave oscillation (DWO) in parallel channels occurs when the slope of the system pressure-drop versus flow rate curve is positive. When one channel is disturbed, the inlet velocity of this channel is reduced which resulting in a decrease of the pressure-drop in this channel. After a time *t*, which is the time taken by a particle to reach the outlet of the channel, the inlet velocity will increase because of the constant pressure-drop boundary. An increased inlet velocity in turn causes the residence time of the particle to go up and a lesser pressure-drop. When the particle reaches the outlet of the channel, a decrease in inlet velocity will be caused and this starts the cycle again. At the same time, an opposite behavior can be observed in another channel for common boundary conditions. Finally, the oscillation of the mass flow between parallel channels is triggered, while the total mass flow of the system remains constant. There are two general approaches to analyze the two-phase flow instability: frequency domain analysis method and time domain analysis method. For the frequency domain (Lahey and Moody, 1977; Fukuda, 1979), the system stability is evaluated with classic control-theory techniques in which the transfer functions are

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Nomenclature

A	cross-sectional area of the control volume (m^2) or matrix
B	matrix
D_e	equivalent diameter (m)
f	fluid or friction pressure drop coefficient
g	vapor or gravitational acceleration (m/s^2)
h	enthalpy (kJ/kg)
k	loss coefficient
N_{pch}	phase change number, $N_{pch} = (Q/W)(v_{fg}/(h_{fg}v_f))$
N_{sub}	inlet subcooling number, $N_{sub} = (\Delta h_{in}/h_{fg})(v_{fg}/v_f)$
p	pressure (Pa)
Q	heating power (W)
t	time (s)
u	velocity (m/s)
W	mass flow rate (kg/s)
z	axial coordinate

Greek symbols

ρ	density (kg/m^3)
ρ_{tp}	mixture density of two-phase fluid
μ	dynamic viscosity (Pa·s)
ϕ^2	two-phase multiplier coefficient
Δ	difference

Subscripts

i	size class
1φ	single-phase region
2φ	two-phase region

obtained from linearization and Laplace-transformation of the governing equations. However, some nonlinear problems can't be solved by the frequency domain analysis method, since it omits some nonlinear information. The two-phase flow instability in parallel channels is a nonlinear problem. Hence, the models built in time domain are applied to analyze the two-phase flow instability. 0D analysis models (Munoz-Cobo et al., 2002; Schlichting et al., 2010) based on the analytical integration of conservation equations in the computing region have been built. In addition, more complex but accurate 1D analysis methods have been developed by some researches (Lee and Pan, 1999; Guo et al., 2008b; Zhang et al., 2009) to study the stability of multiple-parallels system using suited numerical solution techniques (finite differences, finite volumes or finite elements).

In addition, modern methods of nonlinear dynamics were developed by Dokhane et al. (2005, 2007) and Rizwan-Uddin (2006) to investigate the stability analysis of boiling water reactors (BWRs). In their studies, a reduced order model in conjunction with the bifurcation code BIFDD was used to perform the stability and semi-analytical bifurcation analyses of BWRs. Lange et al. (2011) have made great achievements and they developed a RAM–ROM method to study the nonlinear stability analysis of BWRs, where RAM is a synonym for system code and ROM stands for a reduced order model.

Unfortunately, most of them mentioned above have made a hypothesis that the axial heat flux profile on the parallel channels is uniform. In fact, the axial heat flux of fuel channels in the reactor is non-uniform. Hence, it is unsuitable to use the uniform heat flux to analyze the system stability in the reactor cores. Some experimental and numerical works have been carried out on two-phase flow instability under cosine heat flux. Djikam and Sluiter (1971) found that cosine heat flux could stabilize the flow, while Bergles (1976) pointed out that cosine heat flux had a destabilizing effect. Dutta and Doshi (2008) have studied the effect of the axial heat profile on different BWRs and found that a sinusoidal axial heat profile enlarged the stability region. Contradictory results have been obtained by these reports. Therefore, it is necessary to go further on the study of this problem. In this paper, semi-implicit finite-difference scheme and staggered mesh method were adopted to analyze the influence of non-uniform heating on two-phase flow instability in parallel channels. Different axial heat flux profiles such as cosine and bottom-peaked heat fluxes have been studied. The marginal stability boundary (MSB) and the three-dimensional instability space have been obtained under different operation conditions.

2. Theoretical model and numerical method

For our studies, the parallel channels system consists of two plenums and two parallel channels as shown in Fig. 1. The two-phase flow instability in parallel channels will be disturbed by the riser section and inlet section of the channel (Guo et al., 2008a). In order to study the effect of axial non-uniform heating on two-phase flow instability alone, the riser and inlet sections are neglected in this paper. The heating section is composed of two parts which are single-phase section and two-phase section, respectively. The assumptions made in this study are as follows:

(1) The homogeneous flow model is used for two-phase flow
(2) The fluid is in subcooled state at the channel inlet.
(3) The two phases are in thermodynamic equilibrium.
(4) One-dimensional conservation equations in the axial (z) direction are used.
(5) Only bulk boiling is considered and subcooled boiling is neglected.

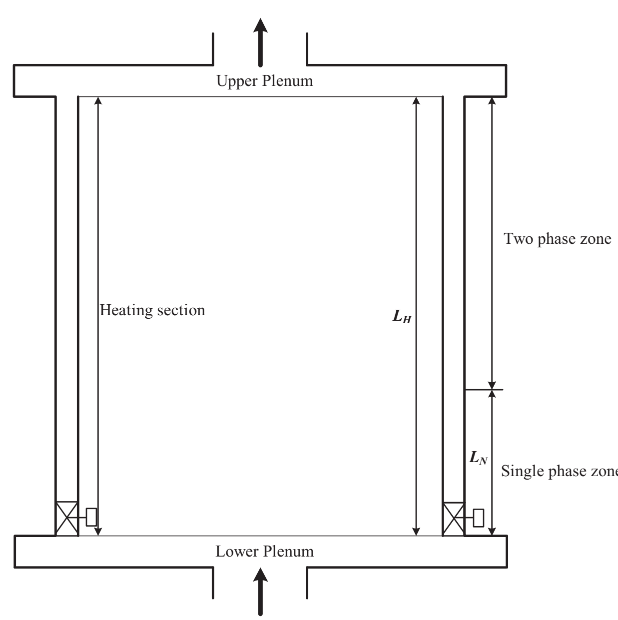

Fig. 1. Schematic of parallel channels system.