International Journal of Heat and Mass Transfer 122 (2018) 1162–1171

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental investigation on flow characteristics of pressure drop oscillations in a closed natural circulation loop

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ARTICLE INFO

Article history:
Received 23 September 2017
Received in revised form 1 February 2018
Accepted 9 February 2018

Keywords:
Pressure drop oscillations
Compressible volume
Flow instability
Natural circulation
Closed loop system

ABSTRACT

An experimental investigation was conducted in a closed natural circulation (NC) loop to study the characteristics of pressure drop oscillations (PDO) under low pressure condition. A 3 × 3 rod bundle channel was used as the test section. The experimental results show that PDO can occur in the closed NC loop when the pressurizer is installed on the upstream of the heating channel. The large amplitude thermal–hydraulic parameters oscillations and reverse flow are the main characteristics for PDO. The oscillation amplitude and reverse flow rate of PDO can be enlarged by increasing the heat flux. Increasing the inlet subcooling degree can help to suppress the PDO occurrence in the closed NC loop. The flow instability boundary is obtain and PDO mainly occurs in the region of the outlet equilibrium quality from −0.008 to 0.012 in present experiment. The interaction between the vapor expansion in the heating channel and the compressibility of pressurizer is the main reason for the occurrence of PDO in the closed NC loop. The effects of compressible volume positions on flow instability was also studied. Moving the pressurizer from the upstream of the heating channel to the downstream can eliminate PDO while density wave oscillations (DWO) can still happen. A tentative explanation for the influence mechanism of compressible volume positions on flow instability in the closed NC loop is reported.

1. Introduction

Two-phase flow instabilities in nuclear reactors can cause system control problems and threaten the safety operation of nuclear power plants. Understanding the characteristics of these instability phenomena and obtaining the stable operating regimes are very important for the safety of nuclear reactors and other two-phase boiling systems. Experimental and numerical researches on two-phase flow instabilities in recent decades are reviewed by Boure et al. [1], Prasad et al. [2], Kakac et al. [3] and Ruspini et al. [4]. Based on these researches, two-phase flow instabilities are usually divided into two main groups: static instabilities and dynamic instabilities. The Ledinegg instability (LED), which can cause flow excursion, is the most studied static instability. For the dynamic instabilities, the widely known are density wave oscillations (DWO), pressure drop oscillations (PDO) and thermal oscillations (THO). PDO usually have longer oscillatory period and are usually accompanied with large amplitude oscillations in pressure and flow rate, which can cause wall temperature oscillations and transient burn-out in heating surface [5]. Therefore, it is very necessary to determine the instability threshold and eliminate the occurrence of PDO in two-phase boiling systems.

After Stenning et al. [6] firstly defined the pressure drop oscillation, experimental and numerical studies on PDO have been widely carried out in following decades. The PDO are generally categorized as compound dynamic instabilities and are caused by the dynamic interaction between the compressible volume and the heating channel. Ozawa et al. [7] analyzed the PDO in a boiling channel system by using a lumped parameter model. They pointed out that the PDO could occurred in a system with a compressible volume, which the pressure drop across the channel decreased with the flow rate increasing in this system. Maulbetsh et al. [8] experimentally investigated PDO and found that the ratios of length to diameter greater than 150 for the heating channel can also trigger PDO without extra compressible volume. Chiapero et al. [5] reviewed the researches done on PDO in single tube, parallel channels and micro-channel systems, and reported that the PDO have different features in vertical channels compared with in horizontal channels. Liu et al. [9] presented a complete analysis of the effect of heat flux, subcooling temperature and surge tank volume on the periods and amplitudes of PDO, DWO and THO. A forced circulation, open loop, upflow system was used in this research. The experimental results were found that the periods and amplitudes of PDO both increased

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.030
0017-9310/

Nomenclature

A_F	flow area (m^2)
D	rod diameter (m)
G	mass flow velocity (kg/m^2 s)
h	enthalpy (kJ/kg)
P	system pressure (MPa)
Q	heating power (kw)
q	heat flux (kw/ m^2)
T_{sub}	inlet subcooling degree (°C)
t_0	average oscillation period (s)
x_e	equilibrium quality
ΔP	pressure drop (kPa)

Greek letters

v	the specific volume (m^3/kg)

Subscripts

f	fluid
g	vapor
i	the initial condition
in	the inlet of test section

with increasing heat flux or decreasing inlet temperature. And they also found reducing the compressible volume could shorten the PDO periods.

Some researchers also analyzed the PDO from the perspective of the non-linear dynamics and bifurcation theory. Padki et al. [10] developed an integral formulation to model the two-phase boiling system and used the total heating power as the bifurcation parameter. Results showed that the magnitude of the negative slope of the steady-state pressure-drop vs. mass flow rate characteristics could be used as the stability criteria for the PDO and the Ledinegg instability. They found that the PDO limit cycles were generated after a super-critical Hopf bifurcation while the Ledinegg instability was caused by a saddle-node bifurcation. Liu et al. [11] conducted the bifurcation analysis and developed a planar system of equations to predict the boundaries of PDO. The inlet mass flow rate of the surge tank was used as the bifurcation parameter. They also found that the PDO limit cycles were generated after supercritical Hopf bifurcation in the two-phase flow system and the limit cycles converge to an asymptotically stable equilibrium point after a reverse supercritical Hopf bifurcation. Srinivas et al. [12] used singularity theory and D-partition method to determine the parameter regions of the occurrence of PDO in a boiling channel. They found the PDO occurred when the operating point was in the positive-slope region of the system pressure drop characteristic and in the negative slope of the channel pressure drop characteristic.

It is worth noting that most of previous studies on PDO have been conducted in the open loops under forced circulation while only a few of them focused on the closed loops. In fact, the practical nuclear reactors are usually the closed circulation systems. For an open loop, the boundary condition on the PDO studies is usually set as the constant inlet and exit pressures. However, the pressure drop boundary in the closed-loop system is always variable. Yu et al. [13]investigated the flow instability behaviors of a rectangular mini-channel in a closed forced circulation loop. The pressurizer provided compressible volume was installed in the upstream of heating channel. Three types of flow instabilities, DWO, PDO and LED were identified and the stability map was obtained. Yu et al. [14] also conducted their experiment under rolling condition and found a new type of instability which was formed by the superposition of trough-type flow oscillation (caused by rolling motion) and PDO. Guo et al. [15] performed an experiment in a closed forced circulation loop with distilled water and used a helically coiled tube as the heating channel. The effects of compressible volume positions on PDO stability boundary and dynamical behavior were analyzed. They found that different surge tank positions corresponded to different oscillation initial boundaries as well as the oscillation periods and amplitudes, and moving the surge tank of the circulation system upstream of the test section could effectively suppress the occurrence of PDO. This conclusion indicates that the compressible volume positions in closed loop becomes an important influence factor on PDO. Based on the above reviews, it can be found that the understanding on the PDO in the closed loop, especially for the influence from compressible volume positions, is still limited.

As an important operation mode, natural circulation (NC) can help to improve the inherent safety of nuclear power plants, which are widely used in the passive safety systems and new designed nuclear reactors [16–18]. The driving head of NC is provided by the buoyancy force due to density difference. Compared to the forced circulation, the NC driving head is relatively small and hard to keep constant, which cause the NC system inherently unstable. The previous researches on the NC flow instabilities were mostly concerned on flow excursion, DWO, flashing instability, geysering and start-up transients [2,19–23]. In a NC system, thermal–hydraulic parameters (including liquid temperature, flow rate, vapor quality and so on) are coupled and interacted with each other to keep the balance between driving force and flow resistance. Once the PDO occurs in the NC loop, the long period and large amplitude oscillations of system parameters can change the flow resistance and hydraulic driving head dramatically. At the same time, the periodical changed driving force can also affect the PDO, which make the system dynamic behaviors become more complex. For the PDO in NC system, only a few of research work can be found in this field. Zhang et al. [24] established a visual natural circulation thermosyphon loop to study the effects of the gas–liquid stratified flow on the thermosyphon loop and investigate the flow pattern transition characteristic. Two scales of oscillations were observed in their experiments. The large scale oscillation was related to the PDO while the small scale was resulted from the flow pattern transition.

In this paper, pressure drop oscillations in a closed natural circulation loop are experimentally analyzed. The aim of this research is to investigate the characteristics of pressure drop oscillations under natural circulation condition and study the effects of thermal–hydraulic parameters and compressible volume positions on the system behavior under PDO condition and obtain the stability boundary.

2. Experimental apparatus and procedure

2.1. Experimental loop and instrumentations

The closed natural circulation experimental loop is schematically illustrated in Fig. 1. It is composed of a 3 × 3 rod bundle test section, a tube-shell type condenser, a pressurizer controlled by filling with nitrogen to adjust and maintain system pressure, a 45 kW preheater to heat the fluid and control the inlet subcooling degree, a centrifugal pump to help establish natural circulation