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Study on flow characteristics in an open two-phase natural circulation loop

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ABSTRACT

Flow characteristics are relevant to the safe operation of natural circulation systems. Experimental research on flow characteristics in an open natural circulation loop was conducted. It was shown that flashing and geysering are the two fundamental phenomena influencing the flow characteristics; in addition, flashing and geysering interact reciprocally: geysering weakens the impact of flashing on the flow, while flashing can suppress geysering. Six circulation modes were identified based on the weight of flashing and geysering, as well as typical inlet flowrate curve and experimental observations. As the heating power varies, so do the weights of flashing and geysering, which result in variable flow behavior and the evolution of circulation modes. Based on the theoretical analysis and the calculation of average circulation flowrate by taking into account the effects of subcooling, flashing and heat dissipation, suggestions for the operating and improvement of the system were proposed.

1. Introduction

Two-phase natural circulation has been widely applied in nuclear power industry due to its passive safety. In the Passive Containment Cooling System (PCCS) of the latest nuclear power plants, two-phase natural circulation is generally adopted as an effective way to remove the heat within the containment in Loss of Coolant Accident (LOCA) or Main Steam Line Break (MSLB) accident, to protect the containment against overheating and overpressure. However, it is found that in the two-phase natural circulation, instabilities may occur, which usually cause unwanted damage to the system, including mechanical vibration of the components and even boiling crisis (Boure et al., 1973). Hence, flow characteristics of two-phase natural circulation are tightly associated with the safety of nuclear power plants.

Since the 1960s, with the development of boiling water reactors, early studies have addressed on two-phase natural circulation and most of them were focused on flow instabilities (Wallis and Heasley, 1961; Jain et al., 1966; Boure et al., 1973; Chexal and Bergles, 1973; Fukuda and Kobori, 1978). Chexal and Bergles (1973) examined flow characteristics of natural circulation in an open loop and seven oscillation regimes were classified primarily based on the bubble behavior. From the 1980s, with the 5 MW nuclear heating reactor, fruitful results on natural circulation at low mass quality and low pressure (Wu et al., 1991, 1997; Jiang et al., 1995) emerged. Wu et al. (1991) classified natural circulation at atmospheric pressure into four patterns: single-phase stable circulation, impulse intermittent oscillation induced by subcooling, unstable flashing and stable flashing. Jiang et al. (1995) elaborated the geysering, flashing instability and low steam quality density wave instability during the start-up of the system, and particularly, the mechanism of flashing instability was interpreted. In the early 21st century, with the improvement of boiling water reactor, a series of experimental and theoretical researches on natural circulation boiling water reactors were conducted (Van Bragt et al., 2002; Manera and Hagen, 2003; Furuya et al., 2005), thus furthering the studies of natural circulation flow characteristics. Manera and Hagen (2003) observed four main types of behavior in the CIRCUS facility at low pressure and low power: stable single-phase circulation, intermittent natural circulation, unstable two-phase circulation and stable two-phase circulation, and they pointed out that flashing could trigger self-sustained flow oscillations. Meanwhile, extensive reviews on two-phase natural circulation instabilities (Boure et al., 1973; Durga Prasad et al., 2007; Ruspini et al., 2014) were presented based on previous work.

Though many contributions have been made to the study on flow instabilities and flow behavior identification of natural circulation, there are relatively inadequate reports on flow characteristics of natural circulation in an open loop (Lee and Lee, 1991; Kyung and Lee, 1994, 1996). Kyung and Lee (1994) analyzed the instability of two-phase natural circulation in an open loop: with the increase of heating power, several circulation modes appeared sequentially, including single phase flow, periodic circulation (A),

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Nomenclature

α	void fraction
$\bar{\alpha}$	average void fraction
C_0	distribution parameter
$c_{f,i}$	velocity of fluid at node i
$c_{f,exit}$	velocity of fluid at the outlet of heating section
g	acceleration of gravity
G	flowrate of steam of cooling water, m^3/h
G_m	mass flux
h_i	specific enthalpy of water at node i, kJ/kg
$h_{s,0}$	specific enthalpy of steam, kJ/kg
$h_{s,1}$	specific enthalpy of the condensed water, kJ/kg
$h_{w,exit}$	specific enthalpy of the water at the outlet, kJ/kg
$h_{w,in}$	specific enthalpy of the water at the inlet, kJ/kg
H_{cold}	height of cold leg, m
H_j	height of the segment j, m
H	the height of the loop, m
H_h	height of heating section, m
K_{in}	inlet resistance coefficient
M_s	mass flowrate of heating steam, kg/s
M_w	mass flowrate of cooling water, kg/s
P	pressure, MPa
p	system pressure, bar
P_{exit}	Pressure at the outlet of heating section, MPa
ΔP_{tp}	two-phase pressure drop, Pa
$\Delta P_{f,tp}$	friction pressure drop, Pa
$\Delta P_{b,tp}$	local pressure drop at the bends, Pa
$\Delta P_{e,tp}$	local pressure drop at enlargements, Pa
$P_{c,sp}$	local pressure drop at contractions, Pa
ΔP	total pressure drop, Pa
ΔP_{sp}	single-phase pressure drop, Pa
ΔP_{tp}	two-phase pressure drop, Pa
ΔP_f	friction pressure drop, Pa
ΔP_a	acceleration pressure drop, Pa
ΔP_l	local resistance pressure drop, Pa
ΔP_{in}	pressure drop in the cold leg of the loop, Pa
ΔP_d	driving head, Pa
q	heat flux, MW/m^2
$q_{dis,i}$	heat dissipation in the control volume i, kJ/k
Q	heating power, kW
Q_v	volumetric flowrate, m^3/h
$Q_{v,ave}$	average volumetric flowrate, m^3/h
t	time, s
T	temperature, °C
T_{exist}	fluid temperature at the outlet of the heating section, °C
T_w	inner wall temperature, °C
$T_{exit,p}$	saturation temperature at the outlet of heating section, °C
T_{exit}	fluid temperature at the outlet of heating section, °C
T_s	saturation temperature, °C
T_s	saturation temperature, °C
v_{in}	velocity of the fluid at inlet, m/s
w_i	the work done by the flow, J
$\bar{W}_{gm}$	weighted drift flux, m/s
x_B	equilibrium steam quality at the steam-generating point
x	steam quality
x_T	the real steam quality at the outlet of the heating section
$x_{fd,i}$	steam quality attributed to flashing and heat dissipation
x_i	total steam quality at node i
z_B	location of the net steam-generating point, m
Δz	height of node i, m
ρ'	density of saturated liquid, kg/m^3
ρ''	density of saturated steam, kg/m^3
$\bar{\rho}_1$	the average fluid density in the downcomer, kg/m^3
$\bar{\rho}_2$	the average fluid density in the riser, kg/m3
σ	surface tension, N/m

continuous circulation and periodic circulation (B); in the mode of periodic circulation (A), the flowrate oscillated periodically, and a stage of single-phase flow (incubation period) existed prior to two-phase flows; periodic circulation (B) was considered as density wave instability. However, compared with other work (Chexal and Bergles, 1973; Wu et al., 1991; Jiang et al., 1995), Kyung and Lee's classification of circulation modes in an open two-phase natural circulation loop seems to be rough and a more detailed classification is necessary. Besides, although Kim and Lee (2000) has claimed that the oscillation mode periodic circulation (A) is the combination of geysering and flashing, like other researchers else (Chexal and Bergles, 1973; Kyung and Lee, 1994), they have neither conducted more thorough researches on the phenomena influencing flow characteristics nor put forward a systematic explanation for the evolution of circulation modes.

In this study, experiments on flow characteristics of natural circulation in an open loop were conducted. The main efforts were focused on examining the fundamental phenomena in a natural circulation, classifying natural circulation modes, and analyzing the evolution of natural circulation.

2. Experimental system and methods

2.1. Experimental system

The experimental apparatus (Fig. 1) consists of the heating system, the circulation loop and the measurement and data acquisition system.

The heating system includes the steam boiler, the air compressor, the pressure vessel, the drain tank. High-temperature mixture of steam and non-condensable gas (air) is injected into the pressure vessel and serves as the heating medium. The steam is generated by the boiler and the air is provided by the compressor.

The circulation loop consists of the heating section, the riser, the downcomer, the horizontal visualization pipe, the water tank and other pipes and valves. The heating section is made of a stainless steel tube, with the length of 2.0 m, outer diameter of 38.0 mm, and thickness of 2.0 mm. For visualization of the experimental phenomena, the riser and the horizontal pipe connecting the riser with the heating section are made of transparent organic glass. Pipes in black in Fig. 1 are coated with thermal insulating materials to reduce heat dissipation of the coolant. Different from the closed loop (Wu et al., 1991; Manera and Hagen, 2003), the circulation loop here is open to the atmosphere via the steam discharging line at the top of water tank. A steam separator is mounted in the water tank to separate two-phase fluid. The steam is discharged into the atmosphere through the discharging line after separation, while the separated liquid is collected by the tank for recycling. The total height of risers is 2.8 m, and the whole system 5.5 m.

The flowrate, temperature, and pressure of fluid are the main thermodynamic parameters to be concerned. The flowrate of heating steam and the cooling water are measured by the vortex flowmeter (±1%) and the electromagnetic flowmeter (±0.5%), respectively. A set of thermocouples (T type, ±0.5%) and pressure transducers (±1%) are arranged along the loop to monitor the temperature and pressure of the fluid. Digital signals of temperature,