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An investigation on flashing-induced natural circulation instabilities based on RELAP5 code

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ABSTRACT

In this investigation, flow instability experiments carried out in a natural circulation loop at the low-pressure condition. Based on experiment data, the RELAP5 code was adopted in the analysis. The objective of this investigation is to get insight into the nature of flashing-induced natural circulation instability. Four typical oscillations observed, intermittent and periodical oscillation, double-peak oscillation, periodical sinusoidal oscillation, and staged irregular oscillation. Under low pressure and low heat flux condition, flashing plays a dominated role in natural circulation oscillation. It is suppressed in higher heat flux. The accumulation of bubbles and fluid inertia result in diverse nonlinear relationship between driving head and kinetic energy. The mechanism of flow instabilities is explored from different aspects. The simulation results of RELAP5 are presented and assessed against the experimental results. The deviation between the results for different circulation modes is discussed as well.

1. Introduction

Natural circulation (NC), as a key issue in nuclear safety, has received considerable attention in a nuclear power plant. It is widely implemented in advanced reactor system such as AP1000 (Schulz, 2006), ESBWR (Zhou et al., 2013) and SWR1000 (Meseth, 2002). Natural circulation under low pressure condition could be used in the heat removal of passive containment. However, two-phase flow instability is likely to occur in low pressure natural circulation system. The flow instability with oscillating parameters could cause many problems such as mechanical vibrations, tube failures and mechanical breakdown.

Boure et al.(1973) firstly reviewed flow instability and followed by other researchers, including March-Leuba and Rey (1993), Kakac and Bon (2008) and Ruspini et al.(2014). It is investigated with many experiments and analyzed with linearized models. The analysis was performed in frequency domain initially (Wallis and Heasley., 1961; Gürgenci et al., 1983). With the advancement of computer code, the numerical investigation has been developing and becomes a mature technology to predict flow instability problem. Using some best-estimate codes in the time domain is more and more practical for these decades. Several codes, such as TRACG, PARET/ANL and TRACE, continuously modified and developed in reactor safety analysis (Andersen et al., 1995; Woodruff et al., 1996; D'Auria and Galassi, 1998; Manera et al., 2005). As the best estimate simulation code, RELAP5 was also evaluated for flow instabilities (Kozmenkov et al., 2012; Fullmer et al., 2016).

A lot of validations of RELAP5 code for flow instabilities were conducted. An assessment of RELAP5 code against static OFI (onset of flow instability) was made by Tewfik Hamidouche and Anis Bousbia-salah (2006). The enhancement of subcooled condensation model and adequate experimental validation under low pressure condition could effectively improve the capabilities of RELAP5 in the prediction. Moreover, flashing and condensation process were validated in stable flow state in a vertical annulus. In the unheated section, condensation and flashing were simultaneously captured with RELAP5/MOD3.3, which could even qualitatively simulate the trend of void fraction variation. Nevertheless, there still existed some errors in the prediction of saturation temperature (Fullmer et al., 2016). Based on the experimental data of CIRCUS facility, the validation of the RELAP5 code for flashing-induced instability was conducted (Kozmenkov et al., 2012). The agreement between calculation results and measurement data might enhance the confidence of RELAP5 code to solve flashing problem under low pressure condition. A more detailed modeling of the components in primary loop could improve the prediction of flow instability remarkably.

It seems to be more reliable to analyze flow instability with RELAP5 code. In the low pressure natural circulation system with

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Nomenclature

A	cross section of flow area (m^2)
d	diameter (mm)
F	driving force (kPa)
h	specific enthalpy (J/kg)
L_h	length of heated channel (m)
L_r	length of riser (m)
M	mass flow rate (kg/s)
Mul	evaporation multiplier
N_{sub}	subcooling number
p	system pressure (MPa)
Q	heating power (kW)
q	heat flux (kW/m^2)
t	time (s)
u	velocity (m/s)
T_{out}	outlet temperature (°C)
T	oscillation period (s)
V	volume
x	equilibrium quality
z	axial coordinate (m)

Greek letters

α	void fraction
Γ	volumetric mass exchange rate (kg/m^3s)
ΔT_{sub}	liquid subcooling (°C)
ε	pumping factor
τ	delay time (s)

Subscripts

avg	average value
bd	boiling delay
cond	condensation
cr	critical
d	downcomer
evapor	evaporation
f	liquid phase
g	vapor phase
h	heated channel
H	height
i	interface
in	channel inlet
l	liquid
out	channel outlet
r	riser
s	saturation
sub	subcooling
w	wall
wg, wf	wall to vapor, wall to liquid

a tall adiabatic chimney, flow instability, which related to flashing, occurs more easily. Considering the particular conditions (low-power and low-pressure) which occurred during start-up, much work has been done to study the nature of flashing-induced instability in research reactors and commercial BWRs such as Dodewaard reactor (Van der Hagen et al., 1997; Van der Hagen et al., 2000).

Since the 1990 s, further studies of flashing instability have been conducted in different experimental facilities. Chiang et al. (1993) clarified three typical instabilities including geysering, DWOs (density wave oscillations), and natural circulation oscillations. Geysering may be induced during start-up of natural circulation BWRs. Aritomi et al. (1993) investigated geysering in parallel to reveal its driving mechanism. The period of geysering is closely related to inlet subcooling and the configure of riser. The mechanism of flashing-induced DWOs in a natural circulation BWR is explained with SIRIUS-N facility (Furuya et al., 2005). Intermittent oscillation and sinusoidal oscillation observed in the experiment turned out to be density wave oscillations. A typical experimental facility called CIRCUS was established to study two-phase flow dynamics for starting-up of natural circulation BWRs (Marcel et al., 2010). Inlet friction was the main factor in their study.

The purpose of this study is to give an insight into the nature of flashing-induced natural circulation instability with RELAP5 code. In low-pressure natural circulation system, flashing-induced instability are observed in the experiment. And then, the analyses of different instabilities are performed by RELAP5 code.

2. Investigation methods

2.1. Experiment apparatus and description

The flow instability experiment was carried out in a natural circulation loop. The experimental apparatus was established in Harbin Engineering University to perform the studies on different principles for natural circulation including axially non-uniform heating, thermal-hydraulics simulation coupled with neutron dynamic, various flow instabilities. It consists of a primary thermal-hydraulic loop, secondary cooling system, data acquisition system and auxiliary experiment devices. The schematic of the experimental apparatus and operating parameters are given in Fig. 1. The conditions are listed in Table 1. The detailed description of experimental facility could also be found in other researches (Chen et al., 2017; Chen et al., 2018).

The primary loop includes heating section, adiabatic riser and downcomer, shell and tube heat exchanger, pressurizer, horizontal pipes and valves. Demineralised water, served as working fluid, heated in a uniform heat flux tube and flows into the tall adiabatic riser. A stainless steel tube adopted as the heating channel with an effective heating length of 1.6 m, the outer diameter of 16.0 mm and thickness of 1.0 mm. There are 21 N-type thermocouples (±0.1%) attached to the outer surface to measure the temperature distribution. Besides, accurate measurement of coolant temperature variation under stable and unstable conditions measured by N-type armored thermocouples (±0.1%), which equipped at the inlet of the test section, riser, and downcomer. Several pressure transducers (±0.1%) and pressure sensors (±0.15%) used to monitor pressure signal of main components. An electromagnetic flowmeter (±0.2%) is installed between the heated channel inlet and pressurizer surge line. The arrangement of flowmeter contributes to capturing negative flow rate when inlet flow reversal occurs and fluid flows back into the pressurizer. In addition, an insulation layer surrounded the entire experimental loop is adopted to reduce heat losses.

The primary loop and the secondary cooling system connected by a shell and tube heat exchanger with counter cooling. It could effectively enhance heat exchange especially when phase transition is intense in the natural circulation system. It is installed at the top of the primary loop. The height difference of 4 m between the thermal center and condenser is helpful to improve natural circulation ability. However, flashing is likely to occur in the tall adiabatic riser and lead to flow instability. Flashing-induced instabilities might happen in nuclear reactor system with the