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Modeling analyses of two-phase flow instabilities for straight and helical tubes in nuclear power plants

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HIGHLIGHTS

- Two-phase flow instabilities in straight and helical tubes were studied.
- The effects of system pressure, mass flux, inlet subcooling on DWO were studied.
- The simulation results are consistent with the experimental results.
- The RELAP5 results are consistent with frequency domain method results.

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ABSTRACT

The effects of system pressure, mass flux and inlet subcooling on two-phase flow instability for the test section consisted of two heated straight channels or two helical channels are studied by means of RELAP5/MOD3.3 and multi-variable frequency domain control theory. The experimental data in two straight channels are used to verify the RELAP5 and multi-variable frequency domain control theory results. The thermal hydraulic behaviors and parametric effects are simulated and compared with the experimental data. The RELAP5 results show that the flow stability increases with the system pressure, mass velocity, and inlet subcooling at high subcoolings. The frequency domain theory presents the same results as those given by the time domain theory (RELAP5). The effects of system pressure, mass velocity and inlet subcooling are simulated to find the difference between the straight and the helical tube flows. The RELAP5 and the multi-variable frequency domain control theory are used in modeling and simulating density wave oscillation to study their advantages and disadvantages in straight and helical tubes.

1. Introduction

The flow instabilities in parallel channels could be classified into two types: static instability and dynamic instability. The latter type, particularly density wave oscillation (DWO) is one of the most common two-phase flow instabilities in nuclear reactor. In extreme circumstances, such as mechanical vibrations and thermal fatigue can be caused by flow rate, system pressure and power oscillations. Straight and helical pipes fit well in different reactors. Some studies show that helical tubes have the advantages of efficient heat transfer performance and small space distribution but higher cost of manufacture is required. Researches on both the straight and helical pipes play a significant role in the security of the nuclear reactor circulation.

Previous studies on the two-phase flow instability mostly focused on the straight channels. Ishii (1976) gave the theoretical basis in DWOs with Ishii-Zuber stability maps. Chang (1996) researched the onset of flow instability in vertical and uniformly heated narrow rectangular channels. In that paper, narrow channels with the advantages of more compact configuration and higher heat transfer efficiency were discussed. The two-phase flow instability in round and rectangle channels was then studied by Guo et al. (2010) and Zhou et al. (2013) using experimental and time domain method. Similar conclusions were given for the effects of flow rate, inlet subcooling and system pressure to DWOs and the instability boundary was reached by the increasing power generation structures. In their papers, RELAP5/MOD3.3 was studied to demonstrate the code capability to reach the DWOs and investigate the dangerous operating conditions by investigating the thermal hydraulic behaviors such as flow rate, vapor generation rate and pressure drop.

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Nomenclature

A	area
C_k	kinematic-wave velocity
C_p	fluid heat capacity
c_0	void distribution parameter
D	coil diameter
d d_h	inner diameter hydraulic diameter
D_k	derived density
$D(s)$	return difference matrix
f	friction coefficient
G_0	mass flux
g	acceleration of gravity
h	enthalpy
I	unit matrix
j	volume velocity of two phase mixture
K^i L	coefficient tube length
N_{pch}	phase change number
N_{sub}	subcooling number
p	system pressure
Δp	pressure drop
P_w	wetted perimeter
Q	heat input
q	heat flux
ΔT_{sub}	subcooling

v	velocity
v_{gj}	drift velocity
w	mass velocity
w_b	critical mass velocity
w_{bh}	critical mass velocity in horizontal pipe
w_{bv}	critical mass velocity in vertical pipe
w_{op}	standard critical mass velocity
X_e	equilibrium quality
α	void fraction
ρ	density
$\rho_c(s)$	closed-loop characteristic polynomial
$\rho_0(s)$	opened-loop characteristic polynomial
θ	transfer function
δ	disturbance quantity
Γ_g	vapor produce rate
Ω	frequency of phase change
Φ_{f_0}	two phase friction multiplier
$\Phi(x)$	two phase local resistance multiplier

Subscripts

g	vapor
in	inlet
l	liquid

Recently some research on the helical tubes was performed with both the time domain method and frequency domain method. Zhou (1992) held that the helical tubes in steam generator have lots of advantages like: (1) vortex flow takes place inside the tube because of the centrifugal force leading to a disturbance in the boundary layer and a better heat transfer performance than the straight tubes; (2) the heat transfer for the compact layout is improved due to the increased surface area; (3) better thermal expansion adaptability which improves the safety and the reliability of the apparatus. To research the flow instability of the two-circuit-coupled DWOs, the multi-input to multi-output transfer matrix is deduced using linearized perturbation theory channels (Niu, 1997). Then by using the modified RELAP5 code, the results of simulations of many experiments performed at several international research laboratories were conducted. Several test sections with different helical diameters were tested to study the effect of the centrifugal forces on the flow pattern. The measured data were the pressure drops along the pipe and the void fraction for different water–air mass flow rate conditions (Castiglia et al., 2012). Furthermore the influence of the helical shape on instability occurrence was investigated by means of a lumped parameter analytical model, which was exploited to highlight some of the peculiarities of DWO phenomena and the respective stability boundary with respect to the classical straight geometry. Experimental campaign results are finally interpreted with a RELAP5 code developed for the prediction of DWO phenomena (Papini et al., 2014).

In this paper, DWOs in straight and helical pipes are studied by the time domain method and the frequency domain method. It aims at finding the advantages and disadvantages of the time domain method and the frequency domain method for researching the two-phase flow instability and the differences between straight and helical pipes for increasing the flow rate, system pressure and inlet subcooling.

Table 1
System parameters in straight channels.

System pressure, p	1.00–10.00 MPa
Inlet rate of flow, w	0.01–0.04 kg/s
Inlet subcooling, ΔT_{sub}	20.0–50.0 °C
Heat input, q	0–837 kW/m^2

2. Numerical simulation

2.1. Time domain method

RELAP5/MOD3.3 code is chosen as a simulation tool for the time domain method to apply to the straight and helical parallel channel system in this paper. Water is used as the test fluid. The system and channel parameters are presented in Tables 1–3 and Figs. 1 and 2. Straight ducts are 1000 mm long and have 25 mm × 2 mm cross section and helical tubes are 6000 mm long and have $\varnothing$12 mm cross section. A direct current heating element is applied, along the wall of constant thickness to provide an essentially uniform heat flux.

Two straight or helical channels are modeled by the RELAP5/MOD3.3 code with two pipes connected to inlet and outlet plena.

Table 2
System parameters in helical channels.

System pressure, p	5.00–8.00 *MPa*
Inlet rate of flow, w	0.01–0.06 kg/s
Inlet subcooling, ΔT_{sub}	20.0–60.0 °C
Heat input, Q	10–95 kW

Table 3
Main geometrical data of the helical channels.

Inner diameter, d	12 mm
Outer diameter	25 mm
Coil diameter, D	1000 mm
Coil pitch	500 mm
Tube length	6000 mm
Heated section length	4500 mm
Riser length	2050 mm