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Two-phase flow and boiling heat transfer in two vertical narrow annuli

Peng Changhong [a,*], Guo Yun [a], Qiu Suizheng [a], Jia Dounan [a], Nie Changhua [b]

[a] *Department of Nuclear & Thermal Power Engineering, Xi'an Jiaotong University, Xian 710049, China*
[b] *Nuclear Power Institute of China, Chengdu 610041, China*

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Abstract

Experimental study associated with two-phase flow and heat transfer during flow boiling in two vertical narrow annuli has been conducted. The parameters examined were: mass flux from 38.8 to 163.1 kg/m^2 s; heat flux from 4.9 to 50.7 kW/m^2 for inside tube and from 4.2 to 78.8 kW/m^2 for outside tube; equilibrium mass quality from 0.02 to 0.88; system pressure from 1.5 to 6.0 MPa. It was found that the boiling heat transfer was strongly influenced by heat flux, while the effect of mass velocity and mass quality were not very significant. This suggested that the boiling heat transfer was mainly via nucleate boiling. The data were used to develop a new correlation for boiling heat transfer in the narrow annuli. In the two-phase flow study, the comparison with the correlation of Chisholm [Chisholm, D., 1967. A theoretical basis for the Lockhart–Martinelli correlation for two-phase flow. Int. J. Heat Mass Transfer 10, 1767–1778] and Mishima and Hibiki [Mishima, K., Hibiki, T., 1996. Some characteristics of air–water two-phase flow in small diameter vertical tubes. Int. J. Multiphase Flow 22, 703–712] indicated that the existing correlations could not predict the two-phase multiplier in the narrow annuli well. Based on the experimental data, a new correlation was developed.

1. Introduction

During the last decades, significant attention has been given to the compact heat exchanger due to special requirements for transfer of high heat flux from narrow space. The compact heat exchangers have the characteristics of high thermal efficiencies, small size, light weight and energy saving and can be used in various industrial processes, such as cooling of electric device and nuclear reactors. One kind of this heat transfer tube in such compact exchangers is the narrow annular channel type. Available data suggest important differences between boiling heat transfer and two-phase flow in the narrow channels as compared to those in the conventional sized channels. The consideration with the compact exchangers is the effects of geometry and size of the flow passage on the flow and heat transfer phenomena.

The prediction of pressure drop during flow boiling is very important in the design of heat exchangers. Knowledge of the two-phase friction characteristics is

* Corresponding author.
E-mail address: pxm321@163.com (P. Changhong).

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Nomenclature

B	modification factor
Bo	boiling number ($q/(G(i_g - i_l))$
d_E	hydraulic diameter (m)
d_H	heated diameter (m)
d_i	outer diameter of inside tube (m)
d_o	inner diameter of outside tube (m)
f	friction factor
F	forced-convection enhancement factor
g	acceleration due to gravity (m/s^2)
G	mass flux (kg/(m^2 s))
h	heat transfer coefficient (W/(m^2 K))
i	enthalpy (J/kg)
i_{tp}	enthalpy of mixture (J/kg)
k	conduction coefficient (W/(m K))
L	lengths between two pressure taps (m)
m	mass flow rate (kg/s)
M	molecular weight, for water, 18
N_{Conf}	confinement number
p	system pressure (MPa)
p_{cr}	critical pressure of water (22.12 MPa)
p_{red}	reduced pressure (p/p_{cr})
Pr	Prandtl number
q	heat flux (W/m^2)
Re	Reynold number
S	nucleate boiling suppression factor
T	temperature (K)
x	equilibrium vapor mass quality
X	Martinelli parameter

Greek symbols

α	void fraction
δ	the width of gap (m)
μ	dynamic viscosity (kg/(s m))
ρ	mass density (kg/m^3)
σ	surface tension (N/m)
Φ_l^2	two-phase multiplier based on single phase liquid flow in the ducts
Φ_{lo}^2	two-phase multiplier based on total single phase liquid flow in the ducts
Φ_v^2	two-phase multiplier based on single phase vapor flow in the ducts

Subscripts

a	accelerative
av	average
f	frictional
g or v	vapor phase
in	inlet
I	inside
o	outside
out	outlet
l	liquid phase
lo	only liquid phase flowing
S	saturated
tt	turbulent–turbulent

essential since it would certainly improve the accuracy of the design of thermal systems. Recently, the flow behavior in small tubes (including the narrow rectangular and annular channels with a hydraulic diameter less than 5 mm) is gaining interest. Two-phase flow in narrow rectangular channels has been studied extensively in recent years (Lowry and Kawaji, 1988; Wambsganss et al., 1991; Lee and Lee, 2001; Mishima and Hibiki, 1996) and significant differences to the two-phase flow in the large channels have been noted. Most of the experimental studies indicated that the widely used correlations for calculation of two-phase frictional pressure drop predicted poorly when applied to the narrow channels. Adiabatic two-phase flow in the annuli has been reported by Lahey and Ohkawa (1989), Kelessidis and Dukler (1989) and Ekberg et al. (1999), Lahey and Ohkawa (1989) measured the local void fraction distribution for various air–water two-phase flow regimes in an eccentric annulus. Indeed, the gas was found to preferentially collect in region of the test section having the largest gap. Kelessidis and Dukler (1989) conducted an experimental study of air–water two-phase flow regimes associated with the concurrent, vertical up-flow in an annulus with the gap of 12.7 mm. They identified five major flow patterns: bubbly, slug, churn, annular and annular-with-lumps. They modified the mechanistic model of Taitel et al. (1980) for application to their vertical annular test section. Ekberg et al. (1999) studied systematically the air–water two-phase flow in horizontal, narrow, concentric annuli. The major two-phase flow patterns observed included bubbly, slug/plug, churn, stratified and annular. The obtained flow regime maps were different from those typically