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Theoretical calculation of the characteristics of annular flow in a rectangular narrow channel

Chong Chen, Pu-zhen Gao *, Si-chao Tan, Han-ying Chen, Chao Xu, Zhi-ting Yu

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, College of Nuclear Science and Technology, Harbin Engineering University, Heilongjiang 150001, PR China

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ABSTRACT

A mathematical separated flow model has been developed that is applicable to the annular two-phase flow in the rectangular narrow channels with peripheral heating. The theoretical annular flow model is based on the fundamental conservation principles: the mass, momentum and energy conservation equations of liquid film, and the momentum conservation equation of the vapor core. Through numerically solving the closed equations, boiling heat transfer coefficient, axial pressure gradient, liquid film thickness and velocity profiles in the liquid film are obtained. A good agreement has been found through comparing the experimental data and theoretically predicted results. The liquid film thickness will decrease with the increase of heat flux and channel width, while increases with increasing flow rate and channel height. The velocity profile in the liquid film is not linear when the thickness of the liquid film is not very thin and it increases with increasing heat flux, while decreases with the increase of mass flow rate and channel size. The effects of heat flux and channel width on velocity in the liquid film are larger than that of mass flow rate. The velocity in liquid film tends towards linear, when the liquid film is mainly in the laminar boundary layer.

1. Introduction

Recent advances in applications such as high performance computer, electronic chips, electrical vehicle power electronics, avionics, and directed energy laser and microwave weapon systems in witch high heat flux will be created and other compact systems such as refrigeration/air conditioning, automobile environment control systems have resulted in a great demand for developing a efficient heat transfer technique to transfer these high heat fluxes (Lee and Lee, 2001; Su et al., 2003; Wang et al., 2012; Kim and Issam, 2014). In order to enhance the heat transfer coefficient of these systems the methods of single-phase forced convection or two-phase flow boiling in small tubes or rectangular narrow channels or lunate channels or annular gaps are used. The experimental results have showed that in small channel or rectangular narrow channel the vapor slug is easy to form due to the accumulation of bubbles, and the annular flows are main flow pattern in rectangular narrow channels (Sun et al., 2001; Du et al., 2012; Xing et al., 2013). Annular flow is an important particular flow pattern in the processes of industry and energy transformation due to the high heat transfer coefficient, and it frequently occurs in a wide range of such parameters as quality, system pressure and flow conditions. In annular flow regime, an inherently liquid film covers the surface of the heated channel while the vapor and the entrained droplets flow into the vapor core. The liquid film structure attached on the inside wall is influenced by such variables as working fluid, system geometry, flow orientation, velocity difference between liquid film and vapor core, etc. A lot of literatures of annular flow in circular tubes or annular gaps are presented up to now (Fossa, 1995; Joseph et al., 1996; Fu and Klausner, 1997; Barbosa Jr. and Hewitt, 2001; Qu and Mudawar, 2003; Okawa et al., 2004; Schubring and Shedd, 2011; Du et al., 2012; Kim and Issam, 2012). Entrainment and deposition are extremely important to the mass, momentum, and energy transfer process for developing a theoretical model of annular flow. Thus, there are plenty of entrainment and deposition in annular flow. Fore and Dukler (1995) used an experimental method to assess the droplet size and velocity distributions in the upward annular flow. The experimental results demonstrate that the mean drop sizes are dependent on liquid flow rate and viscosity, and increasing with increases in both. The gas-droplet slip ratio is approx 80% at the tube centerline, indicating significant axial acceleration. Lopez De Bertodano et al. (1997) performed a series of experiments in a small vertical pipe to measure the entrainment rate of annular

* Corresponding author. Tel./fax: +86 451 82569655.
E-mail addresses: chenchong_2012@163.com (C. Chen), gaopuzhen@hrbeu.edu.cn (P.-z. Gao).

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Nomenclature

A	cross sectional area, m^2
B_o	boiling number
C_p	heat capacity at constant pressure, kJ/(kg °C)
De	hydraulic diameter of channel, m
D_{ep}	liquid droplets deposition rate, kg/(m^2 s)
E_{nt}	liquid droplets entrainment rate, kg/(m^2 s)
G	mass velocity, kg/(m^2 s)
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, kW/(m^2 °C)
h_{fg}	latent heat of vaporization, kJ/kg
h_{in}	inlet enthalpy of the test section, kJ/kg
j	superficial velocity, m/s
L	heating length, m
L_{an}	length of annular flow region, m
P	pressure, MPa
Pr	Prandtl number
P_r	channel periphery, m
q	heat flux, kW/m^2
r	distance from the wall, m
Re	Reynolds number
s	rectangular channel height, m
T	temperature, °C
u	velocity, m/s
w	rectangular channel width, m
W	mass flow rate, kg/(m^2 s)
We	Weber number
X	Martinelli parameter
x_{an}	initial quality of annular flow

Greek letters

α_c	void fraction
δ	liquid film thickness, m
ε	eddy viscosity, m^2/s
η_H	eddy thermal diffusivity, m^2/s
ηl	thermal diffusivity, m^2/s
μ	dynamic viscosity, kg/(ms)
ρ	density, kg/m^3
σ	surface tension, N/m
τ	shear stress, N/m^2
φ	entrained fraction

Subscripts

c	vapor core
cal	pertains to calculated value
exp	pertains to experiment value
E	effective
i	liquid/vapor interface
in	inlet of test section
l	liquid phase
lf	liquid film
sat	saturated state
w	wall

flow, and developed a new model that can be apply to the operating conditions in a boiling water reactor based on the experimental data. Kataoka et al. (2000) thought the droplet entrainment is important to the mass, momentum, energy transfer process in annular two-phase flow and the rate of entrainment and droplet sizes significantly affects the occurrences of the dryout. Based on the experimental data, a new correlation for entrainment rate covering both entrance region and equilibrium region has been developed. The present correlation indicates that the entrainment rate is dependent on the total liquid Reynolds, Weber number, and equilibrium entrainment factor. Lopez De Bertodano et al. (2001) used the two-fluid model to develop a model for the entrainment rate in the annular flow region. The results indicate that the effect of surface tension and density ratio should be taken in account when calculating the entrainment rate. Based on the experimental data, a further correlation is proposed that is valid for low-viscosity fluids in the ripple-annular regime. Okawa et al. (2002) developed a new entrainment rate correlation for accurately predicting the flow rates of liquid film and entrainment droplets in annular two-phase flow. The new correlation is based on the simple assumption that the rate of droplet entrainment is approximately proportional to the ratio of the interfacial shear force to the retaining force of surface tension acting on the phase interface. Pan and Hanratty (2002a,b) in order to research the entrainment rate in vertical gas–liquid annular flows a series of experimental researches are performed. The experiments cover pipe diameters of 1.06–5.72 cm, superficial gas velocities of 20–119 m/s, superficial liquid velocities of 0.012–1.35 m/s, gas densities of 0.27–0.35 kg/m^3 and surface tensions of 0.01–0.073 N/m. The results indicated that the entrainment rate is considered to result from a balance between the rate of atomization of the wall layer and the rate of deposition of drops, both rates decrease with the increase of liquid flow. Okawa and Kataoka (2005), Okawa et al. (2005) used the double film extraction technique to measure the deposition rate and the entrainment rate of droplets in vertical upward annular two-phase flow in a small diameter tube. The result show that the deposition rate was primarily influenced by the concentration of the droplets in vapor core and that the entrainment rate was correlated well with the dimensionless number denoting the ratio of interfacial shear force to surface tension force acting on the surface of liquid film. A new liquid–gas separator was designed and the chemically-based titration method was used by Han et al. (2007) to measure the entrainment fraction in real time. The experiments were performed at low system pressure, and the result indicated that the entrainment fraction increases with the increase of both the liquid and gas flow rates. In order to develop a new entrainment correlation that can predict the entrainment fraction under the high flow and high pressure conditions, a series of experiments were conducted by Sawant et al. (2008, 2009). The results show that the entrainment fraction can be described using the Weber number and liquid phase Reynolds number. The interfacial shear stress is also a very important parameter to the annular flow model, and should be taken into account when calculating the mean liquid film thicknesses, wave height, and the frictional pressure drop in the vapor core. A series of experimental researches of measuring and predicting the interfacial frication factors are conducted by Fukano and Furukawa (1998), Fore et al. (2000), Hajiloo et al. (2001), Belt et al. (2009), the results indicated that the interfacial structure is strongly depend on the liquid viscosity, and with increases of liquid viscosity, the interfacial friction factor decreases if compared under the same mean liquid film thickness, but increase under the same Reynolds number of gas phase. The theoretical model for annular two-phase flow in circular tube, micro-channel or annular gap tube can be found in present literatures such as Fu and Klausner (1997), Qu and Mudawar (2003), Su et al. (2003), Kim and Issam (2012),