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Experiments for liquid phase mass transfer rate in annular regime for a small vertical tube

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Abstract

The double film extraction technique was used to measure the deposition rate and the entrainment rate of droplets for vertical upward annular two-phase flow in a small diameter tube. The test section was a round tube of 5 mm in inside diameter, air and water were used as test fluids and the system pressure was varied within 0.14–0.76 MPa. It was shown in the present experimental conditions that the deposition rate was primarily influenced by the droplet concentration in the gas 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. These results were consistent with available empirical correlations that were developed using the experimental data for larger diameter tubes.

Keywords: Annular flow; Mass transfer rate; Deposition; Entrainment; Small tube; Experiment

1. Introduction

Annular flow is a particularly important flow pattern in gas–liquid two-phase flow since it occurs in a wide range of vapor quality. In this flow pattern, the liquid phase moves partly as a liquid film on the tube wall and partly as droplets in the vapor core. There exists mass transfer between the liquid film and droplets because of the deposition of droplets and the atomization of liquid film. It is known that, to a good approximation, the occurrence of critical heat flux condition in annular regime corresponds to the disappearance of liquid film [1]. Using this knowledge, the film flow analysis that is one of the most successful methods to predict the onset of critical heat flux condition in annular regime was developed [2]. The basic equation used in the film flow analysis is given by

$$\frac{\mathrm{d}G_\mathrm{f}}{\mathrm{d}z} = \frac{4}{D}(m_\mathrm{d} - m_\mathrm{e} - m_\mathrm{v}) \quad (1)$$

where z is the distance along the flow channel, G_f is the mass flux of liquid film, D is the tube diameter; m_d, m_e and m_v are the deposition rate, entrainment rate and vaporization rate per unit area of the tube wall, respectively. If Eq. (1) is integrated from the starting point of annular flow to the exit of heated channel, G_f is given as a function of z. The heat flux that is applied when the local film flowrate becomes sufficiently small is considered as the critical heat flux. It is recognized from Eq. (1) that the valid constitutive relations for m_d and m_e are indispensable in the prediction of critical heat flux with this method.

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Nomenclature

C	droplet concentration in gas core (kg/m^3)
D	tube diameter (m)
E	entrainment fraction
F	correction function for z^*
f	friction factor
G	mass flux (kg/m^{2}s)
g	gravitational acceleration (m/s^2)
J	volumetric flux (m/s)
J^*	dimensionless volumetric flux
k_d	deposition mass transfer coefficient (m/s)
k_{d0}	k_d when z_d approaches zero (m/s)
k_e	proportionality factor for m_e (m/s)
m_d	deposition rate (kg/m^{2}s)
m_e	entrainment rate (kg/m^{2}s)
m_v	vaporization rate (kg/m^{2}s)
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
We	Weber number
z	distance along the channel (m)
z_d	deposition length (m)
z^*	dimensionless deposition length

Greek symbols

δ	film thickness (m)
μ	viscosity (Pa s)
π_e	ratio of interfacial shear force to surface tension force
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

1	first film extraction unit
2	second film extraction unit
c	critical
d	droplet
eq	equilibrium
f	liquid film
g	gas phase
i	interfacial
k	g or l
l	liquid phase
w	wall

A number of experimental measurements for m_d have been reported in literature [3–8]. Several techniques including the film removal and redeposition (double film extraction) method [3–5], the thermal (heat balance) method [6] and the tracer mixing method [7,8] were adopted in the measurements. The principles of these measurement techniques are described by Hewitt [9]. Bennett et al. [10] showed that m_d can also be deduced from the critical heat flux data for the tube with axially non-uniform heating [10–16] if the position for the occurrence of burnout can be specified. The important characteristics of these experiments for m_d are presented in Tables 1 and 2.

In adiabatic experiments, annular flow reaches quasi-equilibrium state sufficiently downstream from the gas–liquid mixing section. In the equilibrium state, the flowrates of liquid film and droplets are almost constant along the channel since m_d is balanced with m_e. Hence, the experimental data for m_d measured in the quasi-equilibrium state is expected the good approximation for m_e [5]. It is also possible to deduce m_e from the experimental data of equilibrium entrainment fraction E_{eq} [17]. In order to express m_d with simple equations, it is generally assumed that m_d is proportional to the droplet concentration in the gas core C through a deposition mass transfer coefficient k_d

$$m_d = k_d C \tag{2}$$

Postulating that the liquid film is thin and the relative velocity between the gas phase and droplets is small, the following relation for equilibrium annular flow is obtained from Eq. (2):

$$m_e \cong m_d = k_d C \cong k_d \frac{\rho_g E_{eq} G_l}{G_g} \tag{3}$$

where ρ_g is the gas density; G_g and G_l are the mass fluxes of gas and liquid phases, respectively. Eq. (3) implies that m_e is calculated from E_{eq} if a reliable correlation for k_d is available. The experiments for E_{eq} available in literature are summarized in Table 3 [3,8,18–27].

Tables 1–3 indicate that the measurements for m_d and m_e were conducted in the varied conditions of test fluids, system pressure and tube size. In particular, the inside diameters of the test section tubes used in these experiments were within 9.5–57.2 mm. In some future nuclear power plants, however, the reduction of hydraulic diameter in the reactor core is planned in order to achieve higher breeding ratio of fissile materials [28–30]. Though there exist several mechanistic models to predict the deposition rate in annular flow [31–34], m_d and m_e are usually estimated from the empirically derived correlations in the film flow analysis since the deposition and entrainment of droplets are extremely complex processes. The validity of the correlations for m_d and m_e in smaller tubes should hence be investigated