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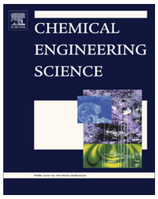

Generalization of droplet entrainment rate correlation for annular flow considering disturbance wave properties

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HIGHLIGHTS

- A mechanical model for droplet entrainment in annular flow is established.
- The mechanism of wave processes on the interface is considered.
- Interfacial disturbance wave effects on droplet entrainment rate is studied.
- Generalization of droplet entrainment rate correlation for annular flow is proposed.

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ABSTRACT

A full knowledge of the interfacial disturbance wave effects on droplet entrainment is crucial for accurately predicting entrainment rate in annular flow. However, most entrainment models in literatures do not account for interfacial properties but only consider global flow parameters than precise wave characteristics. In view of this, based on the shearing-off mechanism of disturbance wave crest, a comprehensive model of droplet entrainment rate for annular flow has been established considering the characteristics of disturbance wave. Effects of hydraulic parameters on the instability of disturbance wave and their relationship with the droplet entrainment rate are presented. Results reveal that the gas and liquid flow rate, hydraulic diameter, surface tension and pressure have a great influence on the wave properties, i.e., critical wavelength, wave amplitude and wave velocity, and hence the droplet entrainment rate. Taking these influencing factors into account, a more accurate and reasonable formula for entrainment rate in annular flow is proposed. Comparison of the present correlation with the existing empirical correlations reveals that the new developed correlation can be correlated reasonably well with the experimental data within ±25% deviation for both air-water and steam-water annular flow.

1. Introduction

Annular gas-liquid flow is of considerable physical interest and great practical significance. This flow is characterized by a thin liquid film adjacent to the wall and a high-speed gas core in the center of the flow. The gas-liquid interface separating the two continuous phases, through which liquid is interchanged with droplet entrainment and re-deposition. As a crucial parameter, the entrainment of the droplets significantly alters the mechanisms of mass, momentum and heat transfer between liquid film and gas core as well as the transfer between two-phase mixture and wall. In order to accurately predict a number of important physical phenomena in annular two-phase flow systems, for example, the critical heat flux and post-critical heat flux in light-water cooled nuclear reactors, the effectiveness of the emergency core cooling systems in water reactors, the droplet carryover in steam boilers and the performance of the film cooling of jets and rocket engines (Ishii and Grolmes, 1975; Holowach et al., 2002), an understanding of entrainment mechanism and an accurate model for entrainment prediction is essential.

With regarding to the literatures available, a large amount of experimental data (Singh et al., 1969; Würtz, 1978; Asali, 1983; Schadel, 1988; Jepson et al., 1989; Okawa and Kataoka, 2005) and models for the prediction of droplet entrainment fraction (Oliemans et al., 1986; Ishii and Mishima, 1989; Sawant et al., 2009; Cioncolini and Thome, 2010, 2012; Al-Sarkhi et al., 2012) and the mass flux of entrained droplets (Ueda, 1979; Hewitt and Govan, 1990; Nigmatulin et al., 1996; Lopez De Bertodano et al., 1997, 2001; Kataoka et al., 2000; Okawa et al., 2002; Okawa and Kataoka, 2005; Baniamerian and Aghanajafi, 2010) in gas-liquid annular flow have been reported. The droplet entrainment data

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Nomenclature

A	cross section area of the pipe, m^2
A_c	interfacial area in the control volume, m^2
A_{entr}	effective drag area, m^2
A_w	wave amplitude, m
A_σ	effective area that surface tension force acts on, m^2
c	wave velocity, $m\ s^{-1}$
C_D	drag coefficient
C_w	coefficient for internal flow
D_h	hydraulic diameter, m
E	entrainment fraction
f_i	interfacial fraction factor
F_d	drag force, N
F_g	gravity force, N
F_σ	surface tension force, N
g	gravitational acceleration, $m\ s^{-2}$
G_l	liquid mass flux, $kg\ m^{-2}\ s^{-1}$
G_f	liquid film mass flux, $kg\ m^{-2}\ s^{-1}$
G_e	entrained droplet mass flux, $kg\ m^{-2}\ s^{-1}$
G_g	gas mass flux, $kg\ m^{-2}\ s^{-1}$
I	intermittency
j	superficial velocity, $m\ s^{-1}$
J	non-uniformity factor
k_E	mass transfer coefficient, $m\ s^{-1}$
K	wave number, m^{-1}
l	length occupied by wave per wavelength, m
M_g	mass flow rate of gas phase, $kg\ s^{-1}$
M_e	mass flow rate of entrained droplets, $kg\ s^{-1}$
N_{cv}	number of waves
N_{ig}	normal stress of gas phase, Pa
N_{il}	normal stress of liquid phase, Pa
N_μ	viscous number
p	pressure, Pa
P_{wetted}	wetted perimeter, m
s	axial position that entrainment occurs, m
S_E	entrainment rate, $kg\ m^{-2}\ s^{-1}$
Re	Reynolds number, $\mathrm{Re}_g = j_g D_h / \nu_g$
t	entrainment period, s
u_f	average velocity of film, $m\ s^{-1}$
$\bar{u}_{gc}$	average velocity of gas core, $m\ s^{-1}$
u_l	average velocity of total liquid, $m\ s^{-1}$
V_{entr}	entrained volume, m^3
We	Weber number
y	distance from the wall, m
$\hat{y}$	amplitude of interfacial disturbance, m
z	axial distance, m

Greek symbols

α	void fraction
δ	film thickness, m
δ_b	base film thickness, m
ζ	correct coefficient
θ	contact angle, °
λ	wavelength, m
μ	dynamic viscosity, $kg\ m^{-1}\ s^{-1}$
ν	kinematic viscosity, $m^2\ s^{-1}$
π	dimensionless parameter
ρ	density, $kg\ m^{-3}$
σ	surface tension, $N\ m^{-1}$
τ	shear stress, Pa
χ	curvature, m^{-1}

Subscripts

avg	average
b	base
c	critical
co	gas core mixture
crest	wave crest
entr	entrainment
E	entrained droplet
f	liquid film
g	gas phase
I	imaginary part
l	liquid phase
R	real part
w	wave

were measured mainly from air-water and adiabatic steam-water flows, which provide a foundation for model development and validation. As for entrainment models, however, due to the complex nature of entrainment phenomenon in annular flow, most of them are empirical in nature and were developed in terms of dimensionless groups considering the equilibrium condition in the fully developed region.

On the other hand, many researchers have demonstrated that there is a clear presence of interfacial wave stability phenomena affecting droplet entrainment in annular flow. Generally, there exist two typical types of waves on the film surface, small-scaled ripple waves and long-length disturbance waves (Hewitt and Hall-Taylor, 1970; Azzopardi, 1997; Alekseenko et al., 2015). At low liquid flow rate, ripple waves dominate the two-phase interface. These ripple waves are short lived and move at low velocities. They usually do not occupy the whole pipe circumference and appear to not carry mass (Schubring and Shedd, 2008; Alekseenko et al., 2009; Belt et al., 2010). When liquid flow rate is large enough, disturbance waves (also called roll waves) with amplitude several times higher than the average liquid film thickness appear in the flow (Andreussi et al., 1985; Azzopardi, 1986). In contrast to small ripple waves, disturbance waves have longer lifespan and carry large mass along the pipe (Hanratty and Hershman, 1961; Asali and Hanratty, 1993; Schubring and Shedd, 2008; Alekseenko et al., 2009; Belt et al., 2010). For annular flow in small diameter pipes $D_h < 60$ mm (Pols et al., 1998), the liquid film is uniformly distributed around the pipe circumference (Asali et al., 1985; Hall-Taylor et al., 2014) and the disturbance waves appear circumferentially coherent (Hewitt and Hall-Taylor, 1970; Asali and Hanratty, 1993; Zhao et al., 2013). Considerable works have been carried out to study the onset of droplet entrainment and the onset of disturbance waves (Hanratty and Hershman, 1961; Zhivaikin, 1962; Ishii and Grolmes, 1975; Azzopardi, 1997; Berna et al., 2014). Relevant results pointed out that droplet entrainment occurs in the region of the main disturbance waves but only a small amount of entrainment occurs in the intervals between the disturbance waves (Hewitt and Hall-Taylor, 1970) (p. 136). This implies that the disturbance waves are a necessary condition for the entrainment of droplets from film surface into the core of gas stream (Cousins and Hewitt, 1968; Azzopardi, 1986, 1997; Han et al., 2006). Ishii and Grolmes (1975) summarized four different mechanisms for droplet entrainment in concurrent gas-liquid flow: roll wave, wave undercutting, bubble burst and liquid impingement. In the case that film Reynolds number is greater than a critical value, i.e., $Re_{fc} = 160$, they suggested that the mechanism of entrainment is basically due to the shearing-off of disturbance wave crests by streaming gas flow. In this mechanism, the drag force acting on the wave tops deforms the interface