International Journal of Heat and Mass Transfer 85 (2015) 265–280

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental and computational investigation of interfacial shear along a wavy two-phase interface

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ARTICLE INFO

Article history:
Received 21 June 2014
Received in revised form 19 January 2015
Accepted 20 January 2015

Keywords:
Interfacial waves
Interfacial viscous drag
Interfacial form drag
Eddy diffusivity

ABSTRACT

This study explores the complex fluid flow behavior adjacent to the interface between parallel layers of gas and liquid. Using water and nitrogen as working fluids, the interface is examined experimentally using high-speed video, and the flow structure predicted using FLUENT. The computational model is used to analyze the gas flow near the interface by isolating and examining a domain that represents an instantaneous snapshot of the wavy interface. Both the observed and computed interfaces show appreciable interfacial waviness, which increases in intensity with increasing flow rates; they also show gas entrainment effects at high flow rates. The computed results show turbulence is completely suppressed along the interface by surface tension. Computed velocity vector plots, contour plots and flow streamlines show interfacial flow separation on the gas side, and these effects are amplified with increasing gas Reynolds number. This produces form drag along the wavy interface in addition to the viscous drag. The interfacial viscous and form drag components increase monotonically with increasing ratio of wave height to wavelength because of the increased frictional resistance and flow separation effects, respectively. A new relation for the interfacial friction factor is derived from the computational results, which agrees well with prior turbulent flow correlations.

1. Introduction

Two-phase flow models incorporate several transport parameters that are represented in terms of fluid properties, flow rates and length scales. However, these models are further complicated by interfacial traits that are not easily predicted. The interfacial wave structure and interfacial dampening of turbulent eddies have been the focus of considerable study [1–3]. These, in turn, influence interfacial velocity and temperature gradient, key ingredients in the development of relations for interfacial mass transfer, shear and heat flux found in theoretical two-phase flow models. The dynamics of fluid flow along turbulent interfaces needs to be investigated in order to resolve the inter-dependent nature of these interfacial parameters.

Interfacial shear can be neglected in the case of free-falling films [4,5]. Where interfacial shear is significant, empirical expressions are incorporated into two-phase models with varying degrees of difficulty, such as the homogeneous equilibrium model and slip-flow model. Empirical relations for interfacial shear aim to account for interfacial momentum transfer due to evaporation or condensation [6], as well as interfacial waviness [6–8]. The pursuit of an improved model for interfacial shear requires systematic assessment of key transport parameters of a turbulent wavy interface, such as both shear and drag forces, eddy diffusivity and length scales associated with a wavy interface.

1.1. Interfacial drag

An examination of literature on the fluid dynamics of two-phase flows shows a far greater focus on interfacial shear as compared to interfacial drag. Ishii and Zuber [9] constructed a unified law for drag coefficient in dispersed flows. Kataoka et al. [10] developed an expression for the interfacial drag coefficient in annular flow, which they used to predict droplet entrainment parameters. Because of the large differences between gas and liquid velocities in annular flow, it is useful to examine drag effects for gas flow along a wavy solid surface. Salvetti et al. [11] studied drag forces exerted along solid sinusoidal surfaces, and consolidated measured and simulated findings from previous studies. Their parametric study considered flow rate, fluid properties and surface profile as salient variables that influence the drag coefficient.

1.2. Interfacial shear in annular two-phase flow

Hartley and Roberts [12] were among the first investigators to recommend a relationship between interfacial friction coefficient,

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.01.096
0017-9310/

Nomenclature

A	local projected interfacial area
C_D	combined (viscous plus form) drag coefficient
$C_{f,D}$	coefficient of viscous drag
$C_{f,i}$	interfacial skin friction coefficient
C_p'	canonical pressure distribution
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$	constants in turbulent kinetic energy transport equation
C_μ	constants in Boussinesq equation
D	hydraulic diameter of entire channel
D_H	hydraulic diameter of liquid layer
$\hat{e}_d$	unit vector parallel to flow direction
$F_{D,form}$	form drag
$F_{D,visv}$	viscous drag
f_g	wall friction factor for Domain 2
f_i	interfacial friction factor
g	gravitational acceleration
h	interfacial wave height
k	turbulent kinetic energy, constant in Stratford [43] separation theory
l	interfacial wavelength
N	number of discrete data points
n	number of samples in subset of data record
$\hat{n}$	unit vector normal to interface
P	pressure; probability
p	probability density
Re	Reynolds number
S	area of curved interface
t	time
$\hat{t}$	unit vector parallel to interface
U	inlet mean x-direction velocity
u_x	x-direction velocity component
$\bar{u}_{x,m}$	local x-direction velocity component averaged over y-span at same location
u_y	y-direction velocity component
u_z	z-direction velocity component
V	inlet y-direction velocity
W	inlet z-direction velocity
x, y, z	spatial coordinates
x'	effective boundary layer length

Greek symbols

δ	annular film thickness
ε	dissipation rate of turbulent kinetic energy
ε_m	eddy momentum diffusivity
μ	dynamic viscosity
ν	kinematic viscosity
ω	turbulent specific dissipation
ρ	density
σ_κ	constant in turbulent kinetic energy transport equation
σ_ε	constant in turbulent dissipation transport equation
τ	shear stress

Subscripts

form	form or pressure (drag)
g	gas
i	interface
l	liquid, laminar
max	maximum
t	turbulent
visc	viscous (drag)
w	wall

Superscripts

$-$	mean component; average
$+$	non-dimensional
$'$	fluctuating component

f_i, and dimensionless film thickness in annular two-phase flow. Wallis [6] developed a theoretical model for interfacial shear, τ_i, in annular flow in terms of flow rate and fluid properties. His model incorporated the influence of drag forces by modifying an expression by Silver and Wallis [13] based on the Reynolds flux concept. Wallis [14,15] later published at a curve fit for f_i that yielded good agreement with pressure drop data for annular flow. Henstock and Hanratty [16] studied air–water annular flow assuming a known entrainment rate, and correlated interfacial shear to the mass flow rate. Using an extensive experimental database, Kataoka et al. [10] updated the Wallis correlation [14] to account for interfacial wave amplitude, which they expressed in terms of f_i and fluid properties. Asali et al. [17] improved this correlation for vertical annular flows by employing an updated technique for measuring annular film thickness in the presence of droplet entrainment.

Narain et al. [18] studied annular condensing flows at different inclinations and proposed an asymptotic model for τ_i that showed good agreement with data. Other published models for τ_i include those of Mickley [19], Shekriladze and Gomelauri [20], Moeck [21], Andreussi [22], Soliman et al. [23], and Spedding and Hand [24]. Fukano and Furukawa [25] investigated the influence of liquid viscosity on interfacial shear in vertical annular upflow, and recommended a correlation for τ_i in terms of f_i and fluid properties. Their unconventional formulation involved higher order terms that accounted for the significant increase in interfacial drag for large film thicknesses. Fore et al. [26] performed experiments involving vertical annular concurrent flow of water and nitrogen to broaden the application range of the Wallis [14] correlation. Their expression demarcated the behavior of f_i at medium and high flow rates, as opposed to the uniform treatment of Wallis [15]. Using a large database and focusing on thick annular films, Wongwises and Kongkiatwanitch [27] recommended yet another correlation for f_i, which accounted for roughness effects over a wider range of flow rates. A common thread observed in all these models is their inability to demarcate the entrainment effects due to phase change from those due to fluid dynamics.

The present study concerns the interfacial characteristics and fluid dynamics of adiabatic horizontal flow of a water film that is shear driven by a nitrogen stream. A facility is constructed to generate a nearly two-dimensional water film whose interface could be captured using high-speed video imaging. Using FLUENT, a computational model is constructed to generate interfacial shape (profile), whose wavy features and turbulence effects are carefully examined. The liquid velocity and interfacial shear stress are inspected to gain detailed insight into their three-dimensional distributions in terms interfacial profile. Skin friction distribution and gas flow separation effects are also examined. A relation is derived for the interfacial friction factor as a function of both liquid film thickness and ratio of wave height to wavelength. Also proposed are relations for the drag coefficient, which can be used to derive criteria for droplet entrainment.

2. Experimental facility

An experimental facility is constructed to study the interfacial structure of horizontal adiabatic water–nitrogen flow. The facility