International Journal of Heat and Mass Transfer 119 (2018) 688–703

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Inter-group mass transfer modeling in the two-group two-fluid model with interfacial area transport equation in condensing flow

Vineet Kumar, Caleb S. Brooks *

Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 6 October 2017
Accepted 16 November 2017

Keywords:
Condensation
Validation
Interfacial area concentration
Void transport
Annulus

ABSTRACT

The two-group two-fluid model with interfacial area transport equation is analyzed in gas-dispersed condensing flow. Past work on the inter-group mass transfer model, required for closure of the dispersed phase conservation equations and interfacial area transport equations, has only considered the condition of expansion of group-1 bubbles to group-2 bubbles with inter-group transfer from group-2 to group-1 only through group-2 breakup. However, in condensing flows, the condensation of large group-2 bubbles provide a significant source of mass and interfacial area to group-1 bubbles. Therefore, the inter-group mass transfer model is revisited in this work to derive a more general form suitable to any heat transfer and pressure change condition. The resulting model requires a second inter-group transfer coefficient. In analogy to the original model, a general case of the group distributions is considered to describe a preliminary treatment of the new inter-group transfer coefficients. The simulation employs a coupled calculation of the void transport equations and interfacial area transport equations for both bubble groups. Validation against existing data shows results consistent with the physics of the flow field.

1. Introduction

The interfacial area transport equation (IATE) has been proposed to satisfy the closure of the interfacial area concentration in the two-fluid model. The two-fluid model, which treats each phase with its own set of conservation equations, relies on interfacial transfer terms to couple the liquid and gas phases. The successful modeling of these transfer terms is a critical assumption in the use of the two-fluid model and is largely predicated on correct representation of the available interface for transfer of mass, momentum, and energy between phases [1]. Not long after the demonstration of the IATE in bubbly flows, the pursuit to capture higher void fraction regimes was met with the realization that modeling small spherical bubbles and large cap/slug bubbles are governed by different mechanisms, requiring separate treatment known as the two-group two-fluid model [2–8]. The two-group model allows for separate description of the transport of group-1 bubbles (i.e. spherical and distorted bubbles) and group-2 bubbles (i.e. cap, slug, and churn-turbulent bubbles) necessitating separate IATE for each group. This expansion in bubble groups also adds an additional set of conservation equations for the gas phase, and therefore correct tracking and partitioning of the gas phase into the bubble groups is critical. The responsibility of this bookkeeping is assigned to an inter-group mass transfer term and is required in the gas phase conservation equations and IATEs. Furthermore, an incorrect definition of the inter-group mass transfer term can lead to physically inconsistent predictions overshadowing the gains obtained in using a two-group/multi-group approach.

The IATE accounts for changes in number density at constant gas volume (interaction mechanisms), changes in number density due to creation/destruction of gas volume (phase change mechanisms) and changes in gas volume at constant number density (gas expansion/contraction mechanisms). In the case of the two-group IATE, the inter-group transfer is an additional term accounting for the change in bubble group identity. Since the bubble group is based on bubble size, with the boundary taken to be the maximum distorted bubble size, a bubble can change its group affiliation through interaction mechanisms, phase change mechanisms, and pressure change.

Considerable progress has been achieved in the mechanistic modeling of bubble interaction mechanisms for adiabatic air-water flows in various configurations [3,9–12]. The interactions mechanisms for bubbly flows principally consist of bubble coalescence due to random collision of bubbles driven by turbulence and bubble breakup due to turbulent impact. The two-group IATE model was later formulated by Ishii and colleagues [2,3] and

---

* Corresponding author at: Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois, 104 South Wright Street, Urbana, IL 61801, USA.
E-mail address: csbrooks@illinois.edu (C.S. Brooks).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.087
0017-9310/

Nomenclature

A	area [m^2]
a_i	interfacial area concentration [1/m]
C_o	distribution parameter [–]
C_∞	asymptotic value of the distribution parameter [–]
c_p	specific heat capacity [J/kg K]
D	diameter [m]
D_h	hydraulic diameter [m]
f	particle distribution function [m^{-6}]
g	acceleration due to gravity [m/s^2]
G	mass flux [kg/m^2 s]
h_{fg}	latent heat of vaporization [J/kg]
Ja	Jakob number [–]
j	superficial velocity [m/s]
m	mass [kg]
Nu_c	condensation Nusselt number [–]
n_b	bubble number density [1/m^3]
P	pressure [Pa]
Pr	Prandtl number [–]
p_c	fraction of bubbles in the inertially controlled region [–]
Re	Reynolds number [–]
S	particle source per unit mixture volume [m^{-6}]
t	time [s]
T	temperature [K]
U	rise velocity [m/s]
V	volume [m^3]
v	local velocity [m/s]
W_G	gap width [m]
z	axial location [m]

Greek

α	void fraction [–]
α_t	thermal diffusivity [m^2/s]
β	non-dimensional bubble diameter [–]
Γ	mass generation rate per unit volume [kg/m^3 s]
ΔT_{sub}	liquid subcooling [K]
Δz	node length [m]
η	volume change rate per unit volume [1/s]
κ	group-2 shape factor [–]
μ	dynamic viscosity [Pa s]
ξ	non-dimensional bubble volume [–]
ρ	density [kg/m^3]
σ	surface tension [N/m]
ϕ	interfacial area source/sink term [1/m s]
χ	inter-group mass transfer coefficient [–]
ψ	shape factor [–]

Subscripts

b	bubble
bc	boundary
CO	inertially controlled condensation
$Conv$	convection
c	critical
DP	pressure change
f	liquid condition
g	vapor (gas) condition
i	interface
in	inlet or inflow condition
j	interface
max	maximum
min	minimum
PC	heat transfer controlled condensation
p	peak
RC	random collision
SO	shearing off
Sm	Sauter mean
sat	saturation condition
TI	turbulent impact
t	total
WE	wake entrainment

Mathematical symbols

‹ ›	area averaged quantity
« »	void fraction weighted area averaged quantity
max()	maximum function
min()	minimum function

substantial effort has gone towards formulating and benchmarking the interactions mechanisms. Ishii et al. [2] proposed five categories of interaction mechanisms for the two-group IATE model: coalescence due to random collisions driven by turbulence, coalescence due to wake entrainment, breakup due to the impact of turbulent eddies, shearing off small bubbles from cap bubbles, and the breakup of large cap bubbles due to flow instability on the bubble surface. Hibiki and Ishii [4] focused on bubbly-to-slug transition and categorized the two-group interaction mechanisms into four groups similar to Ishii et al. [2] but neglected breakup of small bubbles from cap bubbles and the coalescence of small bubbles into cap bubbles as the bubble count in the transition regime was expected to be low in the experimental conditions studied. Hibiki and Ishii [4] proposed the following new two-group interaction mechanisms: coalescence of two cap bubbles due to wake entrainment, coalescence of a spherical/distorted bubble and a cap bubble due to wake entrainment, breakup of a cap bubble into two cap bubbles due to turbulent impact, breakup of a cap bubble into a cap bubble and a small bubble due to turbulent impact. Hibiki and Ishii [4] benchmarked the area-averaged two-group IATE model with upward adiabatic air-water pipe data and obtained excellent predictions for the interfacial area concentration of the bubble-slug transition with an average relative deviation of 3.61%, neglecting inter-group mass transfer due to bubble expansion. Fu and Ishii [5] derived mechanistic two-group interaction mechanisms covering bubbly, slug and churn flow regimes assuming representative cap and slug bubble shapes. Fu and Ishii [5] classified the modeling of the bubble interaction mechanisms for slug/cap bubbles into four major categories: coalescence due to acceleration of trailing group-2 bubbles in the wake region of a leading group-2 bubble, coalescence of group-1 bubbles in the liquid slug to group-2 bubble due to random collision in the wake region driven by high turbulent intensity or by wake entrainment through recirculating vortex structures, shearing off of small bubbles at the skirt of group-2 bubble and break-up of group-2 bubbles due to turbulent disintegration. Fu and Ishii [13] benchmarked the area-averaged two-group IATE model of Fu and Ishii [5] using four sensor conductivity probe data taken for upward air-water pipe flow, neglecting inter-group mass transfer due to bubble expansion. Fu and Ishii [13] determined closure coefficients for the newly proposed group-2 interaction mechanisms using the same dataset and obtained satisfactory results with ~15% error for bubbly-slug flow and slug flow conditions, and ~11% error for churn-turbulent flow conditions. Sun et al. [6] proposed the modified two-fluid two-group IATE model by combining the two gas phase momentum equations into a simplified momentum equation based