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Modeling approaches for strongly non-homogeneous two-phase flows

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Abstract

In some situations, two-phase flows exhibit strongly non-homogeneous behaviors like the one where the flow domain is divided into a bubbly region and a droplet region separated by a free surface. In such a situation, the gas bubbles in the bubbly region and the gas sky in the droplet region can exhibit very different fields of velocity and temperature. The same observation can be made for the liquid droplets and the continuous liquid in the bubbly region. The classical 'two-fluid model' can be too limited in its capabilities to correctly predict such types of flow, especially in the region around the free surface. In this paper, we analyze three different models more adapted to this kind of situation. The first one is a four-field model where one set of balance equations is written for each of the four fields: continuous liquid, continuous gas, liquid droplets and gas bubbles. This model is particularly heavy since it basically contains 12 balance equations. Therefore, two simplified two-field models have been written by summing the equations of the four-field model two by two, in two different ways. In the first two-field model, the equations are summed by region, giving three balance equations for the bubbly mixture and three balance equations for the droplet mixture. In the second two-field model, the equations are summed by phase, giving a model analogous to the usual two-fluid model, but with additional terms coming from the different fields interactions. The closure problem is discussed for each model and the three models are compared according to several criteria.

1. Introduction

During the last decades, two-phase flow studies have occupied an increasing place in industrial and environmental processes, like nuclear technology, chemical and petroleum industries, and others. Numerical tools played an increasing role in this context. These numerical tools can be one-dimensional or three-dimensional in their description of the processes. They generally use the 'two-fluid' six-equation model, or sometimes more simple models like the mixture three-equation model or the diffusion four-equation model (Ishii, 1975; Ishii and Hibiki, 2006). The advantage of the two-fluid model in comparison to more simple models is its ability to deal with mechanical and thermal imbalances.

In some particular situations, one can find strongly non-homogeneous two-phase flows, where the flow is divided into a bubbly region and a droplet region, these two regions being separated by a continuous surface. This can be the case, for example, of an immersed heat-exchanger in a liquid pool. The heat released by the tubes of the immersed exchanger can create bubbles by vaporisation of the liquid phase surrounding the tubes. These bubbles can collapse into the liquid, when moving in a region of the pool where the liquid temperature is lower, or can move up to the free surface before collapsing. In this last situation, we have the simultaneous presence of bubbles and of a free surface, separating the liquid pool and a gas sky, with bubbles bursting at the free surface. Another example is the annular mist flow where one can find a liquid film flowing on the wall together with a gas core carrying liquid droplets. If the wall temperature is sufficiently high, vapour bubbles can also take place in the liquid film. In these two examples, even the two-fluid model can be too limited. In the first example, the gas bubbles and the gas sky can be characterised by very different temperatures and velocities. It is also the case for the droplets and the liquid film in the second example.

Abbreviations: BE, balance equation; CR, closure relation; DFM, drift flux model; DNS, direct numerical simulation; DR, definition relation; EOS, equation of state; LES, large eddy simulation; RANS, Reynolds averaged Navier Stokes; RHS, right hand side; VOF, volume of fluid

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Nomenclature

a_i	volumetric interfacial area
C_D	drag coefficient
d	bubble or droplet diameter
e	specific apparent internal energy
E	total energy interfacial transfer for bubbles and droplets
$\underline{g}$	gravity acceleration
i	specific enthalpy
I	general interfacial transfer for bubbles or droplets
$\underline{J}$	molecular diffusion flux
$\underline{J}^\mathrm{T}$	turbulent diffusion flux
K	kinetic energy
ℓ	latent heat of vaporization
$\underline{M}$	interfacial momentum transfer for bubbles and droplets
$\underline{n}$	unit normal vector
p	pressure
$\underline{q}$	heat flux density
$\underline{q}^\mathrm{T}$	turbulent heat flux density
t	time coordinate
T	temperature
$\underline{\underline{T}}$	stress tensor
$\underline{v}$	velocity
V	control volume
$\underline{x}$	position vector

Greek letters

α	void fraction or local concentration
β	volumetric fraction occupied by the bubbly region
Γ	mass volumetric production rate
λ	conductivity
λ^T	turbulent conductivity
μ	viscosity
μ^T	turbulent viscosity
ρ	density (volumetric mass)
$\underline{\underline{\tau}}$	viscous stress tensor
$\underline{\underline{\tau}}^\mathrm{T}$	turbulent stress tensor
Φ	general body source
χ	characteristic function
ψ	general specific quantity

Indices

b	bubbly region
d	droplet region
g	gas phase
i	interface
k	general phase index
l	liquid phase
m	two-phase mixture
s	free surface
sat	saturation

In order to deal with strongly non-homogeneous two-phase flows, as those we have just described, one can split each phase into two fields: a continuous one and a dispersed one. If one set of mass, momentum and energy balance equations is written for each of these four fields, a model of 12 balance equations, like the four-field model of Lahey and Drew (1999), is obtained. If this model has the advantage to be very general, it has the inconvenient to be very heavy and to need a large number of closure relations. Our goal is