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Interfacial force study on a single bubble in laminar and turbulent flows

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HIGHLIGHTS

- A novel DNS-based approach is verified and validated using correlations and data.
- The influence of bubble deformation level on the bubble motion is investigated.
- Parametric studies on the effect of turbulent flow on the drag force is performed.

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ABSTRACT

Two-phase flows are present in various industrial processes in engineering fields ranging from light water reactor engineering to petrochemical engineering. In this paper, we conduct the interfacial force study on a single bubble under both laminar and turbulent flow scenarios. Advanced finite-element based flow solver (PHASTA) with level-set interface tracking method is used to perform the studies. The interface tracking approach is verified and validated by analyzing the interfacial forces, i.e., drag and lift forces, and comparing the results with the experiment-based data and correlations. The sign change of transverse migration direction is observed at $Eo = 3.4$ which is close to the experimental observations. A set of parametric studies, including relative velocity, bubble deformability and turbulent intensity, are performed to analyze the impact of homogeneous turbulent flow on the drag force. A new drag coefficient closure model is proposed which agrees well with the DNS data considering both laminar and turbulent flow. Those studies can complement the experimental database to obtain improved closure laws for interfacial forces and are important contribution to the multiphase computational fluid dynamics (M-CFD) closure model development.

1. Introduction

As a widely encountered phenomenon in various engineering systems, two-phase flow remains an active topic of research in the nuclear engineering community due to its importance in light water reactors (LWR). Accurate prediction of bubbles' behavior in two-phase flow is important because the pressure drop and heat transfer characteristics of bubbly flow sensitively depend on the void fraction distribution, and more importantly, in boiling flows this distribution affects the on-set of departure from nucleate boiling (DNB) phenomena. While experimental studies allow limited observations of large systems under realistic conditions (e.g. measurement of pressure drop changes and other integral parameters), it is generally difficult to independently achieve full control of the separate force effects and to obtain detailed, microscale data directly usable to develop physics-based models. The advancement in high-performance computing (HPC) and direct numerical simulation (DNS) coupled with interface tracking methods (ITMs) provides reliable analysis tool for the two-phase flow high-fidelity modeling. When properly verified and validated, this approach allows to perform additional studies in larger parametric domain than experiments, and thus help better understand the physics-based trends in bubble/turbulence interactions.

The multiphase computational fluid dynamics (M-CFD) codes heavily rely on the interfacial closure laws to model the bubble distribution and dispersion in the domain. The closure laws normally developed based on experimental data (Tomiyama et al., 2002, 1998) and analytic solutions for very simple conditions. For an excellent interfacial closure law, it should have the following three features: firstly, it is supposed to based onactual physics and can really describe physical phenomena of bubbly flows under different operating scenarios; secondly, the closure law should be a formula as simple and general as possible, and its profile should be continuous and should not show abnormal changes; thirdly, factors influencing the closure law should be taken into account

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Nomenclature

Notation

A	bubble cross-sectional area (m^2)
A'''	interfacial area density (m^{-1})
C_D	drag coefficient
C_L	lift coefficient
C_{TD}	turbulent dispersion coefficient
C_{VM}	virtual mass coefficient
C_W	wall coefficient
$CF_i^{(n)}$	i^{th} component of the control force at time n
d	scalar in re-distancing equation (m)
D	spherical bubble diameter (m)
D_H	extended bubble diameter (m)
E_o	spherical bubble-based Eotvos number
E_oH	extended bubble-based Eotvos number
f	body force
F_D	drag force (N)
F_L	lift force (N)
F_s	safety factor for GCI calculation
F_{TD}	turbulent dispersion force (N)
F_{VM}	virtual mass force (N)
F_W	wall force (N)
g	gravity (m/s^2)
h	grid spacing
H_ε	heaviside kernel function
I	turbulent intensity
k_l	liquid turbulent kinetic energy (m^2/s^2)
M	spacing between two grids (m)
M_k	momentum exchange term of phase k ($kg/(m^2 \cdot s^2)$)
M_k^D	momentum exchange term of phase k caused by drag force ($kg/(m^2 \cdot s^2)$)
M_k^L	momentum exchange term of phase k caused by lift force ($kg/(m^2 \cdot s^2)$)
M_k^{VM}	momentum exchange term of phase k caused by virtual mass force ($kg/(m^2 \cdot s^2)$)
M_k^{TD}	momentum exchange term of phase k caused by turbulence dispersion force ($kg/(m^2 \cdot s^2)$)
M_k^W	momentum exchange term of phase k caused by wall force ($kg/(m^2 \cdot s^2)$)
Mo	Morton number
n	power decay exponent
n_w	unit normal vector
p	pressure (N/m^2) or order of convergence for GCI
Q	q-criterion (s^{-2})
r	grid refinement ratio
Re	Reynolds number
Re_b	bubble Reynolds number
Re_τ	friction Reynolds number
S	strain rate tensor (m/s)
Sr	non-dimensional shear rate (s^{-1})
t	time (s)
v_r	relative velocity between liquid and gas (m/s)
$\vec{w}$	pseudo velocity in re-distancing equation (m/s)
We	Weber number
u'	root-mean-square of the turbulent velocity fluctuations (m/s)
u_g	gas velocity (m/s)
u_l	liquid velocity (m/s)
U_o	mean streamwise velocity in wind tunnel experiment (m/s)
U	mean velocity (m/s)
x	x direction coordinate (m)
x_o	virtual origin (m)

Greek letters

α	void fraction
α_{gs}	void fraction in the small bubble region for
δ	channel width (m)
ε	interface half-thickness in level-set equation (m)
ε_d	interface half-thickness in re-distancing equation (m)
φ	scalar in advection equation (m)
ϕ_{sr}	dimensionless drag multiplier
μ_L	liquid dynamic viscosity ($N \cdot s/m^2$)
ν_l	liquid kinematic viscosity (m^2/s)
ω	shear rate (s^{-1})
Ω	vorticity tensor (s^{-1})
σ	surface tension (N/m)
τ	pseudo time in re-distancing equation (s)
τ_{ij}	viscous stress tensor (N/m^2)
ρ_l	liquid density (kg/m^3)

as comprehensively as possible. Although the experiments provide valuable database for the development and validation of numerical models in the nuclear industry, the rapid advancement of computer power has made the DNS approach feasible in studying complex fluid dynamics problems. Compared with most simulation approaches, DNS solves the Navier-Stokes equations directly without any turbulence closure models. Since its first-principle based, DNS is regarded as a reliable tool to compliment the experiments to develop two-phase closure models.

Among the numerous interfacial forces, drag and lift forces are of special importance, which have direct influence on stream-wise mean velocity and lateral distribution of bubbles in two-phase flows. It has been observed in the experiments that the lateral migration of bubbles strongly depends on the bubble deformability, which typically depends on the bubble size and it can be described by dimensionless number (e.g. Eötvos number). Small, spherical bubbles in upflow condition tend to migrate toward the pipe wall which causes a wall-peaked bubble distribution, whereas large, deformable bubbles tend to migrate towards the pipe center which results in a core-peak bubble distribution (Liu, 1993; Hibiki et al., 2001). Lu and Tryggvason (2008) revealed that this phenomenon is caused by the bubble deformability, not the size of the bubbles by simulating the bubble behavior in turbulent bubbly flow. The migration of bubbles can be explained by the shear-induced lift force model. In this paper, we analyze the lift forces acting on a single bubble in low shear laminar flow (3.8 s^{-1}) and our results are consistent with the experimental observations (Dijkhuizen et al., 2010; Tomiyama et al., 2002).

While the development of closure models for two-phase laminar flow has reached a certain level of confidence, more studies and investigations are required for turbulent flows. In additional to the laminar flow study, we perform the dimensionless study to analyze the impact of homogeneous turbulent flow on the interfacial forces. A set of parametric studies has been performed to quantify the relationship between drag force and typical two-phase turbulent flow parameters, i.e., turbulent intensity, bubble deformability and relative velocity. The ultimate goal of this research is to gain insight on the interfacial forces and improve the existing closure laws. Once the expression for interfacial forces and turbulence are correctly developed, the physics behind the