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Investigation of bubble swarm drag at elevated pressure in a contaminated system

C.D. Lane [a], V. Parisien [b], A. Macchi [b,*], A.A. Donaldson [a,**]

[a] Department of Process Engineering and Applied Science, Dalhousie University, Halifax, NS, Canada
[b] Centre for Catalysis Research and Innovation, Chemical and Biological Engineering Department, University of Ottawa, Ottawa, ON, Canada

HIGHLIGHTS

- Bubble swarm drag investigated at elevated pressure in a contaminated system.
- Individual drag coefficients for bubble size classes within a swarm are found.
- Current swarm drag models are evaluated in a contaminated system at pressure.
- An improved drag correlation for the isolated single bubble is given.
- Elevated pressure data suggest insignificant swarm hindrance effect on drag.

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ABSTRACT

Improved estimates of bubble dynamics in industrial gas-liquid fluid systems are important for accurately modeling multiphase flow. In many gas-liquid industrial systems at elevated pressure, bubbles exist in a polydisperse size population. This work experimentally characterizes the effects of bubble swarm polydispersity and gas holdup on drag using a monofibre optical probe in an ethanol contaminated aqueous system, providing an evaluation of current swarm drag models under industrially relevant pressures and high gas holdup conditions (up to 37% gas fraction). At atmospheric pressure, the rise velocity and swarm-corrected drag of individual bubbles within a polydisperse distribution of bubbles was found to be well-predicted by the swarm correction model of Lockett and Kirkpatrick (1975). An improved fit to the reported data was found using a piecewise isolated single bubble drag coefficient correlation. At elevated pressures (6.5 MPa), swarm hindrance effects were not observed for detected bubbles and the rise velocity and drag coefficient of individual bubbles within a polydisperse distribution were well predicted without the use of a swarm correction model.

1. Introduction

Modeling multi-phase flow is important for a broad range of chemical processes and unit operations. Computational fluid dynamics (CFD) is commonly used to predict fluid flow in complex geometries. Currently, in the field of multi-phase flow CFD, population balance models (PBM) are being used to provide more fidelity to gas-liquid systems that contain a dispersed phase with a non-negligible size distribution (Bhole et al., 2008). Of particular interest for industrial scale process simulations are Euler-Euler and Euler-Lagrange type solvers due to the relatively low computational cost for large simulated domains. These solvers reduce computational requirements by utilizing momentum coupling terms that are semi-empirical by nature, and thus it is important that these terms have high accuracy and robustness in order to ensure good simulation fidelity. Of the numerous proposed momentum coupling terms, drag is of particular importance. However, most drag correlations were developed for single isolated bubbles. More recent work extended these models to poly-dispersed bubbles traveling in a swarm where correction factors to the single isolated bubble drag correlations are proposed. Initial work by Davidson and Harrison (1966); Bridge et al. (1964), and Lockett and Kirkpatrick (1975) applied the well-known Richardson–Zaki correlation for gas-solid flow to gas-liquid flow. These correlations were presented as phase velocity corrections, not as drag models, and therefore implementation requires the selection of an unhindered/isolated bubble rise velocity value. Alternatively, more recent works by Garnier et al. (2002); Behzadi et al. (2004); Simonnet et al. (2007), and Roghair et al. (2011), (2013b), (2013a),

* Corresponding author.
** Corresponding author.
E-mail addresses: arturo.macchi@uottawa.ca (A. Macchi), adam.donaldson@dal.ca (A.A. Donaldson).

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Nomenclature

$A_{projected}$	Projected area of bubble
A_r	Cross-sectional area of radial position r
C_D	Drag coefficient for a single bubble in a swarm
$C_{D\infty}$	Drag coefficient for an isolated single bubble in a quiescent liquid
$C_{D,swarm}$	Swarm drag coefficient correction factor
d_c	Bubble chord length
d_b	Bubble diameter
dP/dX	Pressure drop along length of column
dV	Differential volume
E	Bubble shape factor
F_D	Force due to drag
F_P	Force due to pressure (buoyant force)
F_G	Force due to gravity
g	Gravitational acceleration
L_s	Sensing length (instrumentation calibration value)
N	Number of bubbles in volume
n_b	Number of bubbles
t_b	Time-on-probe
t_r	Rise time
u_b	Bubble rise velocity
$u_{b\infty}$	Single isolated bubble rise velocity
u_s	Bubble slip velocity (relative velocity to liquid interstitial velocity)
$\bar{u_b}$	Average bubble velocity
$u_{l,avg}$	Interstitial liquid phase velocity
α	Gas holdup
ρ_l	Liquid phase density
ρ_g	Gas phase density
i	Bubble class size i
r	Denotes radial position r

have used modern experimental and numerical techniques to propose swarm corrections to the isolated bubble drag coefficient.

Fig. 1 illustrates various swarm correction factors applied to the drag coefficient of a single bubble in a swarm. While there is reasonable agreement between correlations at gas holdups below 5%, they diverge by as much as 130% (not including the Simonnet et al. model) at a gas holdup of 40%. The correlation proposed by Simonnet et al. (2007) deviates from the general increasing trend of the other models, attributed to a change in flow regime, where the onset of larger bubbles from coalescence allows for cooperative rise and therefore decreases the overall effective drag in the bubble swarm.

Consensus on a single correlation for swarm conditions appears to be elusive partly due to isolating the contributing factors that affect the drag on a bubble in a swarm. This study investigates which model is best suited for estimating drag on bubbles in systems with contaminated fluids at both atmospheric and high pressure operating conditions where relatively small bubbles (<1.0 mm in diameter) constitute a large portion of the bubble population. Such small bubbles have not been measured when developing the swarm drag models, yet are commonly found in pressurized industrial scale processes with inherently multi-component fluid flow.

The experimental conditions and single bubble models used to develop the investigated bubble swarm models are summarized in Table 1. Of these studies, only Garnier et al., Behzadi et al., and Lockett and Kirkpatrick have experimentally presented data for gas holdups above 25%. As shown in Fig. 1, experimental data at very high gas holdup conditions ($>15\%$) is of importance as the correlations show significant deviation from one another in this range. However, experimentally achieving gas holdup conditions above 15% is difficult without transitioning to the coalesced bubble flow regime such as that encountered by Simonnet et al. This is primarily due to the smaller diameter columns in lab scale experimental setups and associated difficulty of maintaining the bubble-to-column diameter ratio to prevent flow regime transition into coalesced flow at gas holdups greater than 15% (Shah et al., 1982). The high gas holdup region is critical for many industrial scale operations as the larger length scales delay the onset of coalesced bubble flow to higher gas fractions as well as induces less non-uniformity and effects from near-wall conditions to the flow field. It is therefore important that drag closures are capable of accurate prediction at high gas holdup when modeling gas-liquid flow at these scales.

The swarm drag correction factor is applied to a single isolated bubble drag coefficient. Typically, a monodisperse assumption is made, assuming all bubbles in the swarm are of equal size, and the mean bubble diameter of the swarm is selected to determine the average rise velocity. This method assumes that all bubble sizes

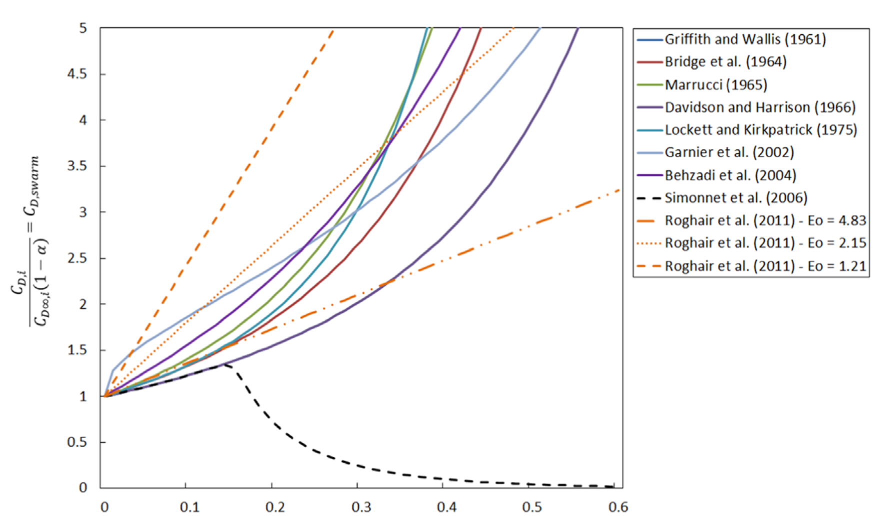

Fig. 1. Current swarm correction correlations based on a single bubble model.