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Bubble swarm rise velocity in fluidized beds

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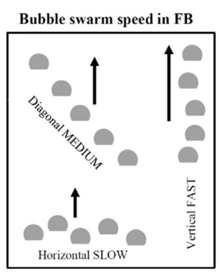
HIGHLIGHTS

- New approach to the 'excess-gas-velocity' problem.
- New formulas for bubble swarm speed based on collective added mass.
- Relation between bubble spatial arrangement and bubble swarm speed.

GRAPHICAL ABSTRACT



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ABSTRACT

New formulas are suggested for the swarm speed of cap-shaped gas bubbles collectively rising within a gas–solid fluidized bed. Their derivation stems from comparing the added mass of a single bubble and a swarm of bubbles:

$$\frac{U_B}{U_0} = \sqrt{\frac{C_0}{C}}.$$

For different flow conditions, there are different trends in the dependence of the added mass on the bubble concentration (voidage). This variance translates into different predictions of the suggested swarm speed formulas. This difference is explained in terms of the geometrical configuration of bubbles inside the bed. The expressions for the added mass coefficient in case of two typical flow regimes are introduced:

$C = C_0(1 - \varepsilon)$ freely bubbling regime,

$C = C_0(1 - \varepsilon)^2$ near slugging regime.

1. Introduction

Many characteristic features of fluidized beds (FB) are dominated by the behaviour of gas bubbles. The understanding of the bubble behaviour is therefore of crucial importance for the design and operation of fluidized bed reactors (Fan and Zhu, 1998, Gidaspow, 1994, Jackson, 2000, Kunii and Levenspiel, 1991, Pell, 1990, Yates, 1983). Of the many complex aspects of the bubbling FB (bubble origin, formation, rise, coalescence, breakup, transport, reaction, etc.; see e.g. Davidson et al. (1977) and Jackson (2000, Chapt. 5)), here we focus on the collective bubble rise velocity in gas–solid FB in the bubbling regime. The two-phase mixture (gas + fine solids) is considered as a single homogeneous pseudo-phase called the 'emulsion phase' (index e). The 'gas bubbles' (index b) are the regions depleted from particles where the particle content is sufficiently low to qualify them as discrete 'voids' in the emulsion phase. The gas bubbles are considered as the light fluid 'dispersed particles' moving/rising through the 'continuous phase' of the carrying dense emulsion, see the definition sketch in Fig. 1. Our goal is to suggest new formulas for the collective velocity (swarm speed) of these bubbles.

The first step is to find U_0, the free-rise velocity of an isolated spherical-cap bubble of size D in an infinite uniform gas–solid medium (emulsion phase). There is the classical empirical result

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Notation

a,b	empirical parameters in Eq. (2.5.1) [dimensionless]
A	aspect ratio of numerical box [dimensionless]
B	energy coupling coefficient [dimensionless]
C	added mass coefficient, C_0 – single particle, $C_{1,2,3,4}$ see Section 2.3 [dimensionless]
D	bubble diameter (equivalent spherical) [m]
g	gravity [m/s^2]
G	gas input [m^3/s]
$k_{1,2}$	parameters in Eq. (1.4).
K	empirical constant in Eq. (2.1.4) [dimensionless]
L	height of fluidized bed [m]
R	bubble radius [m]
r	radial coordinate [m]
s	vertical distance (bubble above orifice) [m]
t	time [s], d/dt – time derivative [1/s]
U	linear, superficial velocity of feed gas, $\Delta U = U - U_{mf}$ [m/s]
U_B	swarm bubble velocity [m/s]
U_0	single bubble velocity (terminal speed) [m/s]
U_{mf}	linear velocity at minimum fluidization [m/s]
u_b	mean velocity of dispersed phase (discrete bubble phase) [m/s]
u_e	mean velocity of continuous phase (carrying emulsion phase) [m/s]
V	volume [m^3]
W	kinetic energy [J], w – per unit volume [J/m^3]
x,y	dimensions of numerical box [m]
α	cap angle [deg]
ε	bed voidage [dimensionless]
ρ	density [kg/m^3]
ψ, ϑ	parameters in Eq. (1.3).

Subscripts

0	isolated body, single bubble
B	bubble(s)
b	bubble phase
e	emulsion phase
mf	minimum fluidization

Abbreviations

FB	fluidized bed

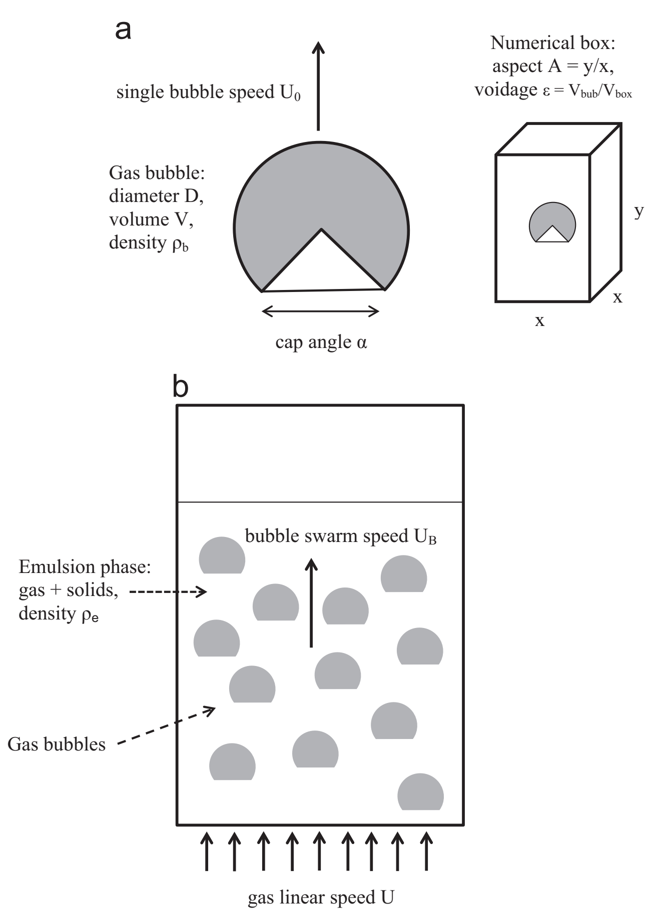

Fig. 1. Definition sketch. (a) A single (isolated) gas bubble of size D, volume V, cap angle α, density ρ_b, rises freely at its terminal velocity U_0 through the emulsion phase in FB. Rectangular numerical box (x–x–y) with aspect ratio $A = y/x$ and with voidage ε=(bubble volume)/(box volume). (b) Fluidized bed with a swarm of gas bubbles rising collectively at speed U_B through the emulsion phase (pseudo-continuum: gas+solid particles) of density ρ_e. The solids are fluidized by the linear (superficial) gas velocity U. The gas bubbles form certain spatial configurations (arrangement patterns) where a tendency to vertical and horizontal clusters can manifest. The cluster geometry can affect the collective rise speed.

by Davies and Taylor (1950) (see also Davidson and Harrison (1963)):

$$U_0 = 0.71\sqrt{gD} \quad \text{(single bubble)} \tag{1.1}$$

The *basic scaling* $U_0 \sim (g.D)^{0.5}$ was obtained from the potential flow theory. Below we will proceed in a similar way and suggest a somewhat modified procedure how to find it. The *numerical coefficient* 0.71 can be obtained from the force balance, if the drag factor of the bubble is known for the typically cap-shaped bubbles. Usually, it is determined by experiments.

The second step is to find the collective rise speed U_B when the bubbles move in a swarm. Several choices can be found in the literature, of which the most common is the empirical formula by Davidson and Harrison (1963):

$$U_B = U_0 + \Delta U, \quad \Delta U = U - U_{mf} \quad \text{(swarm of bubbles)} \tag{1.2}$$

The bubble swarm speed U_B is supposed to be larger than the single bubble speed U_0 by an increment $\Delta U = (U - U_{mf})$, called the *excess gas velocity*. It follows that in the state of minimum fluidization ($U = U_{mf}$), a bubble in the bubble swarm would rise as an isolated bubble, which may seem counter-intuitive, because the collective swarm effect would disappear. Therefore, some additional 'increment' should be considered. On the other hand, the above given increment in Eq. (1.2) may be too large, to contradict the data. We could not find a direct experimental support for Eq. (1.2) in the literature. For instance, Rowe (1971) noted on Eq. (1.2): *"…There is a little experimental evidence to support* Eq. (1.2) *and it is probably the most useful relationship we can presently use…"*. The uncertainty about the use of the increment ΔU is well known in the fluidized bed community and the situation has not changed much during the last few decades, as expressed by Yates (1983, Chapt. 1.6): *"…Although the validity of* Eq. (1.2) *is doubtful it is widely used in reactor design calculations …"*. Often using the increment is a matter of personal choice, as seen in Kunii and Levenspiel (1991, Chapt. 6): *"…Whenever the rise velocity can be represented by either* Eq. (1.1) *or* Eq. (1.2)*, we will use* Eq. (1.2) *because it represents the more conservative estimate for design purposes…"*. Despite its common use, in some situations the increment seems needless. For instance, Müller et al. (2007) employed the ultra-fast