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Bed expansion and multi-bubble behavior of gas-liquid-solid micro-fluidized beds in sub-millimeter capillary

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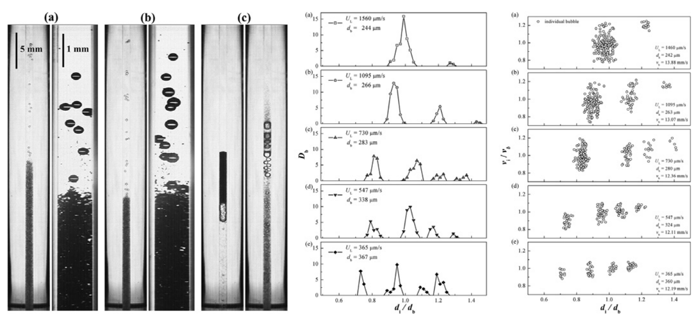
HIGHLIGHTS

- The coalesced bubble flow was identified from the multi-bubble flow.
- The bubble size follows a specific step-type distribution.
- The wall effect has impact on the coalescence of bubbles.
- The larger coalesced bubbles dominate the rise velocity of the multi-bubble flow.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrodynamic study was performed on the gas-liquid-solid micro-fluidized beds with 0.8 mm bed diameter and multi-bubbles through high speed camera recording system. Flow regimes including dispersed bubble flow, coalesced bubble flow and slug flow were identified from the multi-bubble flow. Wall effect at the small bed-to-particle diameter ratio led to the occurrence of bubble coalescence and flow regime transition at lower solid holdups. Obvious bed contraction appeared only at lower liquid velocities or higher gas velocities. The diameter range of the spherical micro-bubbles in the micro-fluidized beds was 200–500 μm. The bubble size in dispersed bubble flow was normally distributed and slightly increased with the solid holdup. And in coalesced bubble flow, the bubble size was decided by the overall coalescence probability and presented a special step distribution. The larger coalesced bubbles concentrated the distribution of bubble terminal velocity. And the bubble terminal velocity decreased with the solid holdup and inversely with the bubble size. In dispersed bubble flow regime, there was positive linear relationship between the apparent viscosity and the solid holdup. Three-phase micro-fluidized beds meet the further development of micro-reactors, and this study on the hydrodynamic characteristics contributes to their wider application.

1. Introduction

The gas-liquid and liquid-liquid flows in the milli- or micro-channels recently have been widely researched, due to the demonstrated excellent transfer performance and controllability [1–3]. As for the mini- or micro-reactors applied to the multi-phase systems involving a solid phase, a variety of efforts such as the modification of flow channel wall [4,5] or the fabrication of extra inner

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Nomenclature

C_D	drag coefficient
D_b	bubble size distribution function based on number frequency of bubbles
D_v	bubble terminal velocity distribution function based on number frequency of bubbles
d_b	average bubble diameter, μm
d_i	individual bubble diameter, μm
d_o	orifice diameter, μm
d_p	average particle diameter, μm
F_B	effective buoyancy, N
F_C	particle-bubble collision force, N
F_D	liquid drag, N
$F_{I,g}$	bubble inertial force, N
$F_{I,m}$	suspension inertial force, N
F_M	gas momentum force, N
F_σ	surface tension, N
H_0	initial bed height, mm
H	expanded bed height, mm
U_E	expansion velocity, μm/s
U_G	superficial gas velocity, μm/s
U_L	superficial liquid velocity, μm/s
U_o	gas orifice velocity, μm/s
v_b	absolute bubble terminal velocity, mm/s
v_i	individual bubble terminal velocity, mm/s
v_r	relative bubble terminal velocity, mm/s

Greek letters

ε	holdup / voidage
μ	viscosity, Pa·s
θ	contact angel
ρ	density, kg/m^3
σ	surface tension, N/m

Dimensionless group

Fr	Froude number, ($Fr = U^2/gd$)
Re	Reynolds number, ($Re = \rho Ud/\mu$)

Subscripts

b	bubble
G, g	gas phase
i	individual
L, l	liquid phase
m	liquid-solid mixture
s	solid phase
o	orifice
p	particle
r	relative

micro-structure [6–8] have been made to introduce the solid interface. Besides, the extending of the conventional particle technology into this micro-scale situation through an approach of micro-packed beds has also been proved to be a feasible option [9–12]. The filled particles not only provide the high specific surface area of solid phase but also intensify the fluid mixing. Thereby, the fluidized beds in the micro-channels or capillaries, i.e. the micro-fluidized beds, can be put forward as another approach. It is because the fluidized beds possess the additional advantages of lower pressure drop and easier loading or removal of solid particles. So the idea of micro-fluidized beds meets the further development needs of both the micro-reactors and conventional fluidized beds.

Compared with the gas-liquid-solid micro-fluidized beds, a lot of researches have been reported on the gas-solid and liquid-solid micro-fluidized beds, because of the lower complexity of these systems. The principal experimental methods included the conventional pressure drop analysis [13] and the visual observation via high speed camera recording system [14]. The main focus of the work is on the determination of the hydrodynamic parameters of the micro-fluidized beds, such as the solid holdup [15,16], the minimum fluidization velocity, the minimum bubbling velocity and the terminal velocity [17,18]. The investigation on the effects of column diameter, bed height and particle properties etc. [19,20] and the comparison between the conventional and micro-fluidized beds were also involved. In the explanation of the differences resulting from the miniaturization, the concept of wall effect was referred to summarize the impact from the increase of the wall friction and the bed voidage. Additionally, considering the advantages of the high wall flux of heat and light, the applications of the pyrolysis [21–23] and photo-catalysis reaction [24] in micro-fluidized beds were also studied.

However, researches on the miniaturization of the gas-liquid-solid fluidized beds are still in the incipient stage. The single bubble behavior in the three-phase mini-fluidized beds has been studied [25]. The visual experiments were performed in the bed columns fabricated based on the transparent rectangular milli-channels of 2–10 mm and the single stainless needle with an outlet diameter over a hundred microns was used as the gas orifice. The formation process of bubbles in two stages and the asymmetric bubble wake were observed. The spherical shape of the bubbles was confirmed and the measured size was in a range of 1.6–2.5 mm. The various effects on bubble size including the liquid and gas velocities, the bed diameter and the liquid and particle properties were determined and discussed. The bubble size was considered to be dominated by the surface tension and the suspension inertial force, and the wall effect also played an important role by reducing the solid holdup. The initial fluidization states for the gas-liquid-solid mini-fluidized beds with circular bed columns of 3–10 mm inner diameters were investigated in another work through the pressure drop analysis and the visual observation [26]. The minimum fluidization velocities in the 8–10 mm mini-fluidized beds were determined, but not in the 3–5 mm mini-fluidized beds due to the half-fluidization state existing between the fixed and fluidized bed. The bubble growth behavior under the initial fluidization state was affected by the liquid-solid mixture properties, the bed diameter and initial height. The initially generated bubbles were different in the shape, size and rise velocity. These led to their different reducing effects on the minimum fluidization velocity.

The three-phase micro-fluidized beds have great potential to enhance the performance of the exothermic and photo-catalytic reactions, because of the great specific interphase and wall areas. And their small reaction volume can improve the safety and controllability of the fast reactions. From the present research status, it can be found that many basic hydrodynamics of the three-phase micro-fluidized beds have not yet been systematically investigated. Especially for the micro-fluidized beds with an extremely small bed diameter and multi-bubbles, the studies are more necessary because of the higher complexity and application value. And the hydrodynamic characteristics different from the conventional fluidized beds also need a comprehensive discussion. So in this