Experiments and numerical simulations of hydrodynamics in gas-liquid-solid mini-fluidized beds

Mingyan LIU[1,2*]

[1] School of Chemical Engineering and Technology, Tianjin University, Tianjin 300350, China; [2] State Key Laboratory of Chemical Engineering (Tianjin University), Tianjin 300350, China

May 25-31, Guilin, China

天津大學
Tianjin University

Outline

1 Introduction

2 Experimental

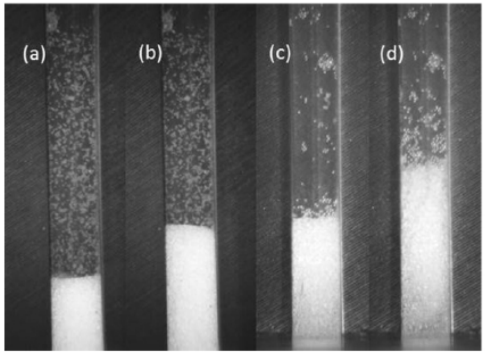
3 Results and Discussion

4 Concluding Remarks

1. Introduction

Multi-phase (G/L/S) fluidization

- ➢ Important unit operation for process industries.
- ➢ High mixing, mass and heat transfer and reaction performances.
- ➢ Efficient and green process are still highly expected.

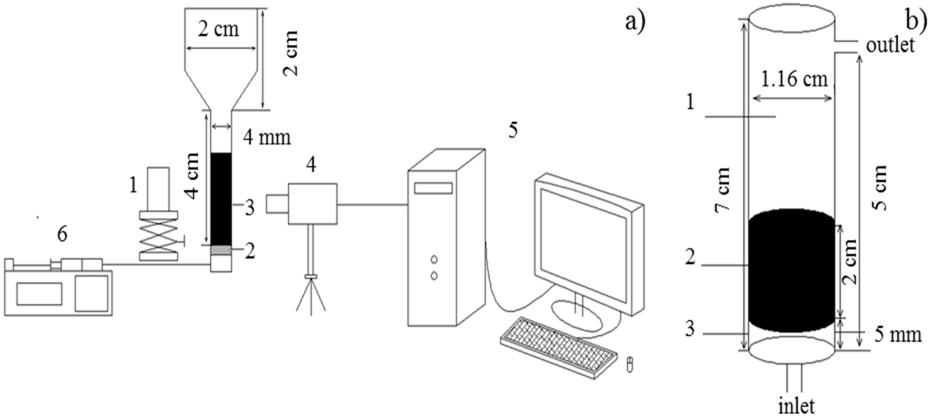


Miniaturization is a process intensification

Size reduction also finds interesting behaviors

Like nano-/micro-/mini- systems

But most microsystems with no fluidized solid particles.



Solid particles added into the nano-/micro-/mini-systems and are fluidized, will form ...

Nano-/micro-/mini- fluidized beds

- ➢ Including G-S, L-S, G-L-S systems.
- ➢ Combining the advantages of a fluidized bed and a nano-/mini/micro-system.
- ➢ Particularly suitable for performing chemical reactions under conditions that would normally lead to some rate limits and unsafe operations.

➢ Expand the research area of solid fluidization.

- The process can be intensified with higher mixing, mass and heat transfer and reaction rates, which are often problematic issues in the microsystems given the laminar nature of the micro-scale flows.
- Suitable for reaction kinetics research and catalyst screening.
- Better process controllability.
- Better process safety.

[1] Can Tang, Liu Mingyan, Li Yanjun. Particuology, 2016, 27:102-109.
[2] Orlando L. do Nascimento, David A. Reay, Vladimir Zivkovic, Powder Technology, 2016, 304: 55-62.

1.Introduction

- **Present published papers on the nano/micro/mini-fluidized beds:**

  Totally, more than 80.

  G-S, 44; L-S 28; G-L-S, 9; G-L, 1.

- **In these systems, flow, mixing, mass and heat transfer and reaction behaviors are different.**

☐G-S micro-fluidized bed bed

✓Ye et al. (2005) report on 3D numerical simulations based on the soft-sphere discrete particle model of GeldartA particles in a 3D gas-solid micro-fluidized bed with bed size of 12.0 ×3.0 ×1.2 mm. The effects of the sidewalls on the hydrodynamics inside fluidized beds were studied and it has been found that the generation of the overshoot of the pressure drop near the minimum fluidization point is affected by both the particle–wall friction and the inter-particle van der Waals forces.

✓Hou and Ge (2007) suggested and studied the gas-solid nano-fluidization under high gravity by pseudo-particle modeling simulations.

✓Guo et al. (2009) reported the gas-solid fluidization characteristics of quartz sand and fluid catalytic crack (FCC) catalyst particles in six micro-fluidized beds with bed inner diameters of 4.3, 5.5, 10.5, 15.5, 20.5, and 25.5 mm. The equations of pressure drop for conventional fluidized beds did not fit for micro-fluidized beds. U_{mf} increased with decreasing bed diameter.

✓Rao et al. (2010) studied the effect of bed diameter and bed height on minimum fluidization velocity in the gas-solid micro-fluidized bed.

✓Wang and Fan (2011) studied the wall effects using FCC particles in six mini- and microchannels with sizes ranging from 700 μm to 5 mm. A increase in the minimum fluidization and bubbling velocities as well as the wall friction. Correlations for predicting the fluidization regime transition in large fluidized beds are not adequate for predicting that in the mini- and microchannels. Also, there is regime transition instability.

✓McDonough et al (2019) report the fluidization in small-scale gas-solid 3D-printed fluidized beds.

✓Xu et al, (2008-) have carried out **systematical** researches on gas-solid micro-fluidized beds, including flow, mixing and reactions and thermo-gravimetric analysis, shown in his oral presentation.

1.Introduction

☐ L-S micro-fluidized bed bed

✓Haynes et al. (1991) mentioned a novel liquid fluidized bed micro-reactor to experimentally study the coal liquefaction.

✓Potic et al. (2005) firstly study the process of biomass gasification in a compressed liquid-solid micro-fluidized bed with bed diameter of 1.0 mm. Different flow regimes as those in the macro-fluidized bed were observed provided D_b/d_p>12. 3D simulations were also carried out.

✓Derksen (2008,2009, 2015) carried out the numerical simulations of the mixing and mass transfer in a liquid fluidized micro-channel.

✓Doroodchi et al. (2012,2013) studied the fluidization behavior in terms of pressure drop, bed expansion and minimum fluidization velocity in capillary tubes with inner diameters of 0.8, 1.2 and 17.1 mm. As the bed diameter reduces the bed voidage sharply increases leading to a reduction in the pressure drop across the bed. Mixing performance of the micro-fluidized bed in terms of mixing time was also investigated using a dye dilution technique.

✓**Zivkovic** et al. (2013-) have done **systematical** investigations on the hydrodynamics and mixing in the liquid-solid expanded and circulating micro-fluidized bed, especially exploring the influence of surface forces and wall effects on the minimum fluidization velocity.

✓Tang et al, (2016) and Li et al. (2018) identified and explained the wall effects in the liquid–solid micro-fluidized bed.

✓Yang et al. studied the photocatalytic activity and scale-up effect in liquid–solid mini-fluidized bed were also studied.

✓Pereiro et al. (2017,2018) studied microfluidic magnetic liquid-solid fluidized bed for DNA analysis in continuous flow mode and for solid phase extraction.

✓Guo et al. (2017) studied the hydrodynamics in the liquid-solid micro-fluidized bed.

1.Introduction

☐ G-L/G-L-S micro-fluidized bed bed

✓[1] Li Yanjun, **Liu** Mingyan, Li Xiangnan. **Minimum fluidization velocity** in gas-liquid-solid mini-fluidized beds. AIChE Journal, 2016, 62:1940-1957.

✓[2] Li Yanjun, **Liu** Mingyan, Li Xiangnan. **Single bubble behavior** in gas-liquid-solid mini-fluidized beds. Chemical Engineering Journal, 2016, 286: 497-507.

✓[3] Li Yanjun, **Liu** Mingyan, Li Xiangnan. Flow regimes in gas-liquid-solid mini-fluidized beds with single gas orifice, Powder Technology, 2018, 333: 293–303.

✓[4] Li Xiangnan, **Liu** Mingyan, Li Yanjun. Bed expansion and **multi-bubble behavior** of gas-liquid-solid micro-fluidized beds in sub-millimeter capillary, Chemical Engineering Journal, 2017, 328:1122-1138.

✓[5] Li Xiangnan, **Liu** Mingyan, Ma Yongli, Dong Tingting,Yao Dong. Experiments and **meso-scale modeling** of phase holdups and bubble behavior in gas-liquid-solid mini-fluidized beds, Chemical Engineering Science, 2018, 192: 725–738.

✓[6] Yao Dong, **Liu** Mingyan, Li Xiangnan. **Residence time distributions** of liquid phase in gas-liquid-solid mini-fluidized bed, CIESC Journal, 2018, 69(11): 4754-4762.

✓[7] Yang Zhongguo, **Liu** Mingyan, Wang Xiaoyun. Experiment study and modeling of novel **mini-bubble column** photocatalytic reactor with multiple micro-bubbles, Chemical Engineering & Processing: Process Intensification, 2018, 124: 269–281. **(G-L)**

✓[8] Wang Xiaoyun, **Liu** Mingyan, Yang Zhongguo. Coupled model based on radiation transfer and reaction kinetics of gas–liquid–solid **photocatalytic mini-fluidized bed**, Chemical Engineering Research and Design, 2018, 134: 172–185.

✓[9] Dong Tingting, **Liu** Mingyan, Li Xiangnan, Zahid Saima. **Catalytic oxidation** of crotonaldehyde to crotonic acid in a gas-liquid-solid mini-fluidized bed, Powder Technology, 2019, 352: 32–41.

✓[10] Liu Yuanxing, Zhu Litao, **Luo** Zhenghong, Tang Jiaxun. **Effect of spatial radiation distribution** on photocatalytic oxidation of methylene blue in gas-liquid-solid mini-fluidized beds, Chemical Engineering Journal, 2019, 370: 1154–1168.

1.Introduction

Our studies on the gas-liquid-solid mini-fluidized beds

- Hydrodynamics:

Flow pattern, minimum fluidization velocity, bubble behavior and phase holdup of gas-liquid-solid mini-fluidized bed.

- Numerical simulations

Using VOF-DEM approach, the formation and rising motion of a single bubble were simulated numerically.

2. Experimental

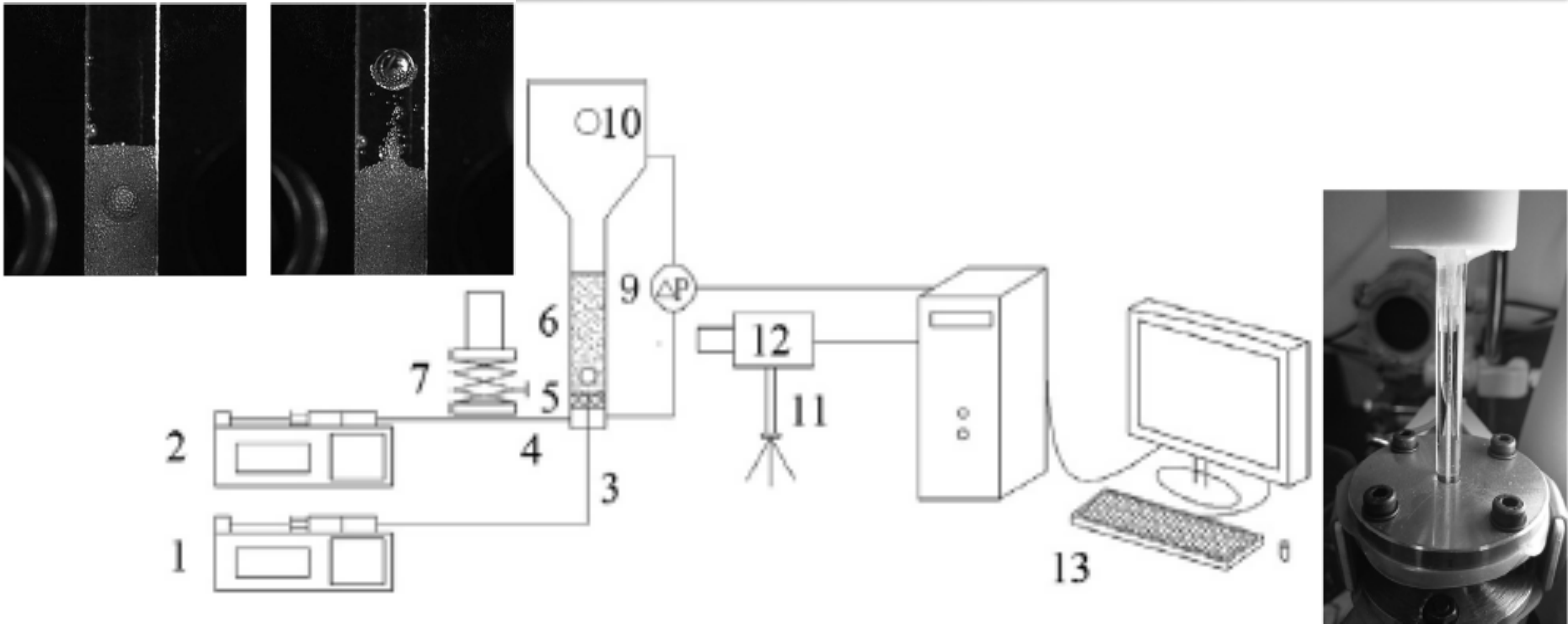
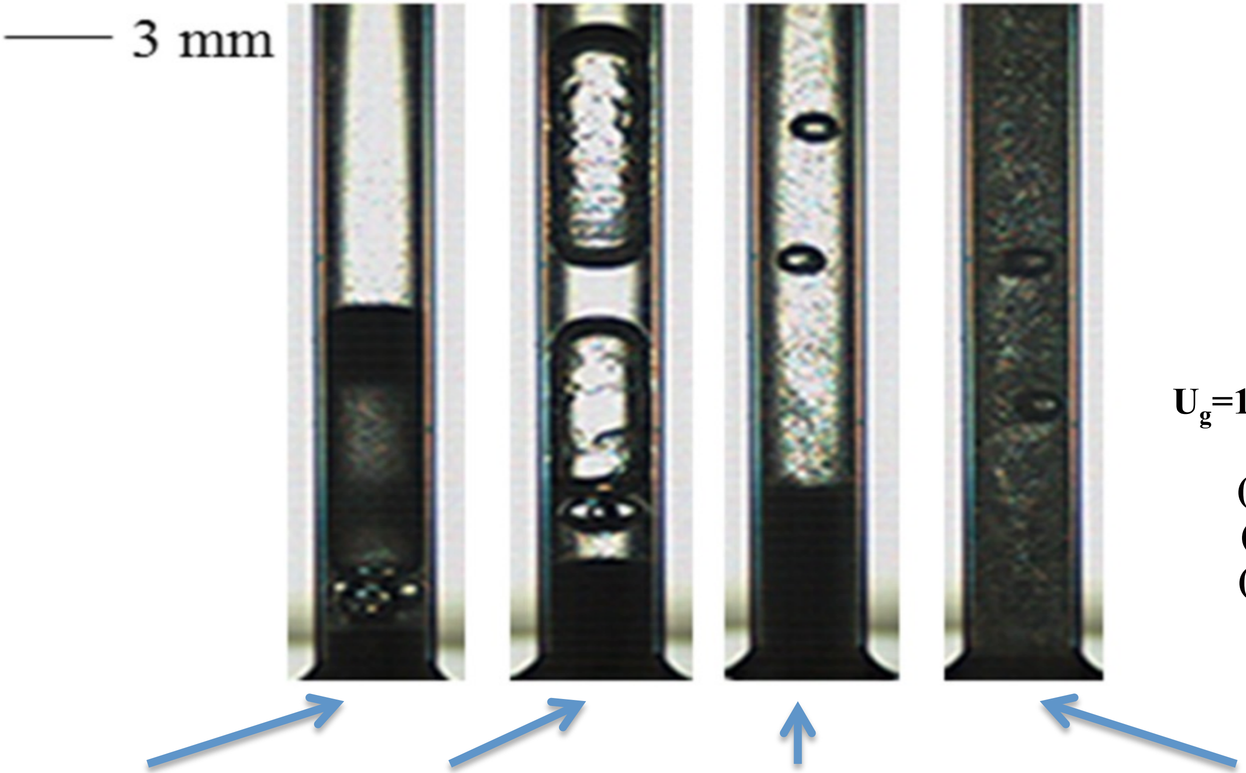


Fig. 1. Schematic diagram of the gas–liquid–solid MFBs. (1) Gas syringe pump; (2) liquid syringe pump; (3) gas inlet; (4) liquid inlet; (5) liquid distribution; (6) test section; (7) lifting platform; (8) cold light source; (9) pressure transducer (for pressure measurement of liquid–solid and gas–liquid–solid cylindrical MFB); (10) outlet; (11) tripod; (12) CMOS camera; (13) computer.

3. Results and Discussion

3.1 Hydrodynamics

3.1.1 Flow patterns in gas-liquid-solid mini-fluidized beds.



$U_g=1.2\times10^{-3}$ m/s, $\rho_p=2500$ kg/ m^3, $H_s=8.5$ mm;
(a) $U_l=7.86\times10^{-5}$ m/s;
(b)$U_l=2.36\times10^{-4}$ m/s;
(c) $U_l=7.86\times10^{-4}$ m/s;
(d)$U_l=7.1\times10^{-3}$ m/s

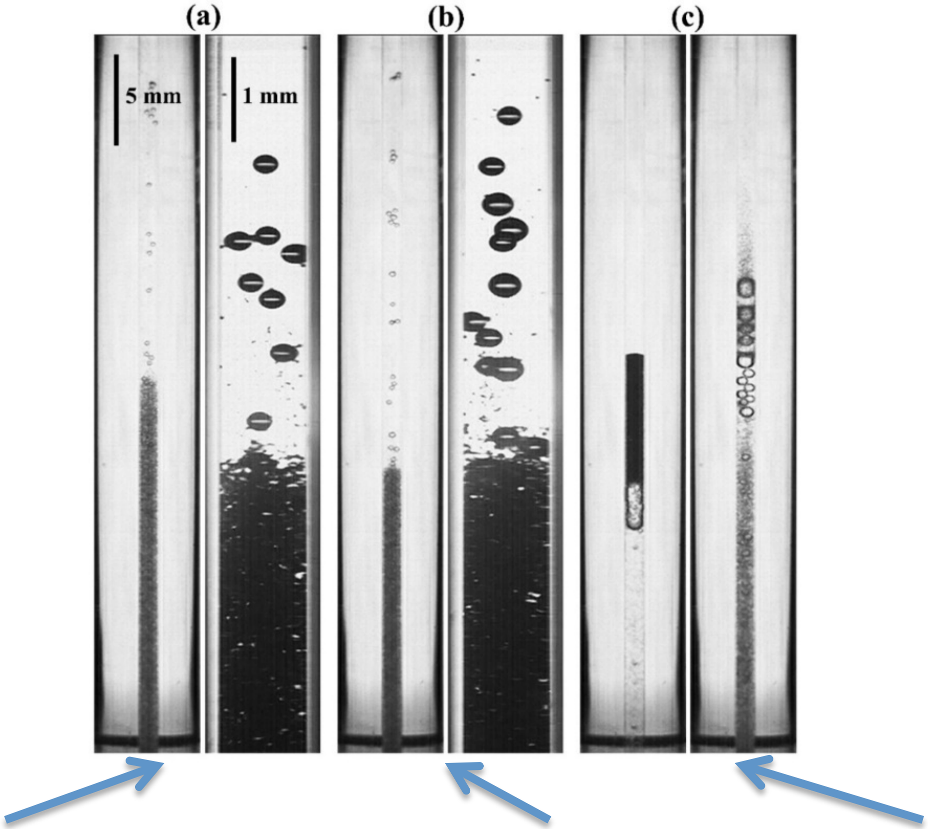
Half fluidization, Slug flow, Dispersed bubble flow, Liquid transport flow

Figure 1a. Representative photographs of flow regimes in a 3 mm gas-liquid-solid mini-fluidized bed.

3. Results and Discussion

3.1 Hydrodynamics

3.1.1 Flow patterns in gas-liquid-solid mini-fluidized beds.



Dispersed bubble flow **Coalesced bubble flow** **Slug flow**

Figure 1b. Typical pictures of flow patterns in a 0.8 mm gas-liquid-solid mini-fluidized bed.

3. Results and Discussion

3.1 Hydrodynamics

3.1.2 Pressure drop and Hurst exponent of differential pressure signal in a 10mm fluidized bed.

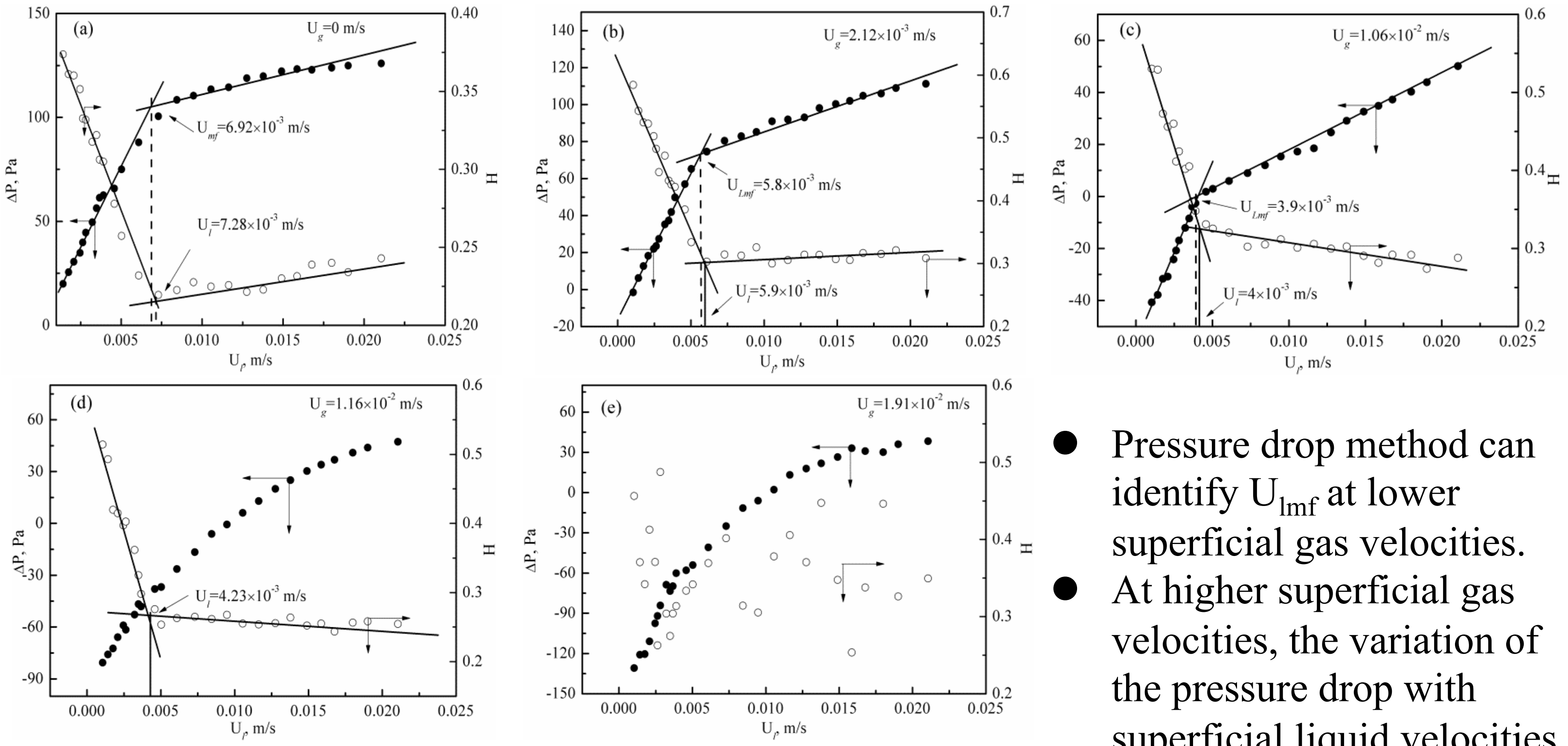


Figure 2. Pressure drop and Hurst exponent of differential pressure signal in a 10mm gas-liquid-solid MFB with superficial liquid velocity at varied superficial gas velocities.

- Pressure drop method can identify U_{lmf} at lower superficial gas velocities.
- At higher superficial gas velocities, the variation of the pressure drop with superficial liquid velocities is smooth, which results in the failure to judge U_{lmf}.

3. Results and Discussion

3.1 Hydrodynamics (with a bubble from the orifice)

3.1.3 Minimum fluidization velocity of gas-liquid-solid mini-fluidized beds. （U_{Lmf}）

Minimum fluidization velocity varing with superficial gas velocity, liquid velocity, solid particle properties and static bed height in the 3-10 mm diameter gas-liquid-solid micro-fluidized bed were studied and correlations were suggested.

U_{Lmf} in a three-phase micro-fluidized bed

$$\mathrm{Re}_{Lmf} = 0.103 Ar^{2.7933} Fr^{-0.1984} \left(\frac{D_h}{d_p}\right)^{-1.5192} \left(\frac{H_s}{D_h}\right)^{0.8938} \left(\frac{\sigma_l}{\sigma_w}\right)^{0.0323}$$

$$\mathrm{Re}_{Lmf} < 1$$

$$\mathrm{Re}_{Lmf} = 7.2159 Ar^{0.4582} Fr^{-0.079} \left(\frac{D_h}{d_p}\right)^{-1.0276} \left(\frac{H_s}{D_h}\right)^{0.1948} \left(\frac{\sigma_l}{\sigma_w}\right)^{-0.3988}$$

$$1 \le \mathrm{Re}_{Lmf} \le 120$$

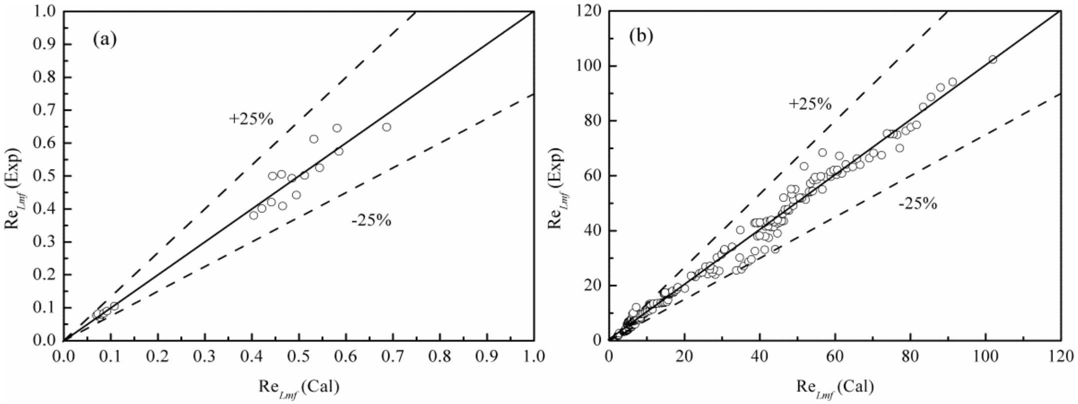


Figure 3. Comparison between predicted data by suggested correlation and experimental results of U_{Lmf} in gas-liquid-solid mini-fluidized beds.
(a) for small solid particles; (b) for large solid particles

3. Results and Discussion

3.1 Hydrodynamics

3.1.4 Single bubble behavior in gas-liquid-solid mini-fluidized beds.

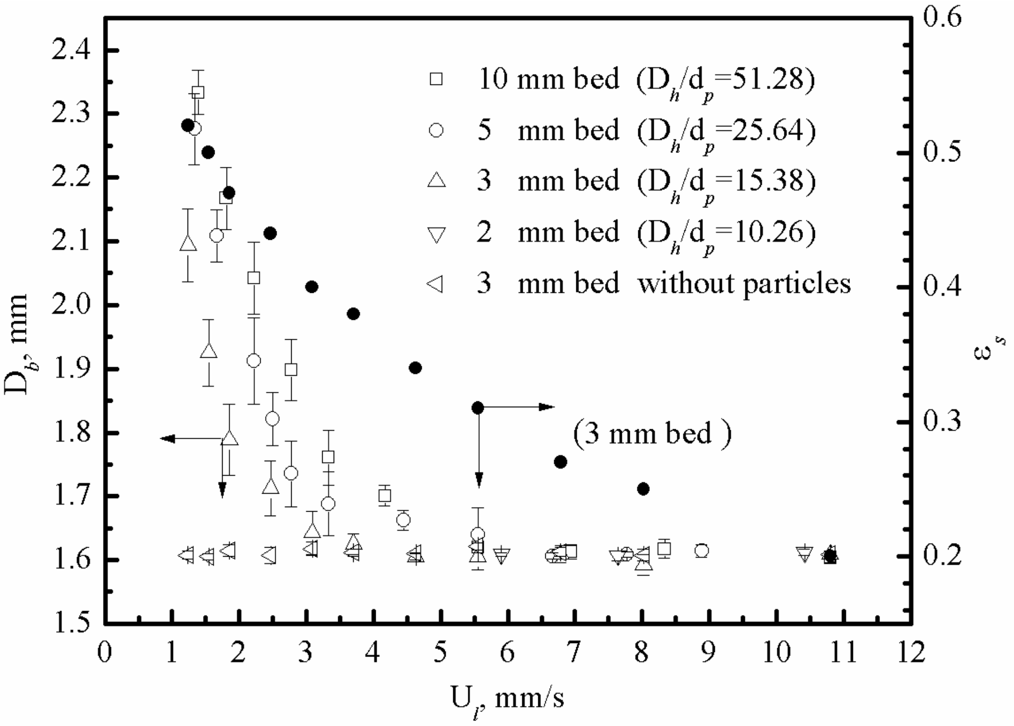


Figure 4. The variation of single bubble size with varied superficial liquid velocities and bed diameters in gas–liquid–solid MFBs

- Superficial liquid velocity ↑, solid holdup ↓, shear stress of liquid-solid suspension ↓, bubble size ↓

- Under higher solid holdup, an increase in the ratio of bed diameter to particle size will result in an increase in bubble size.

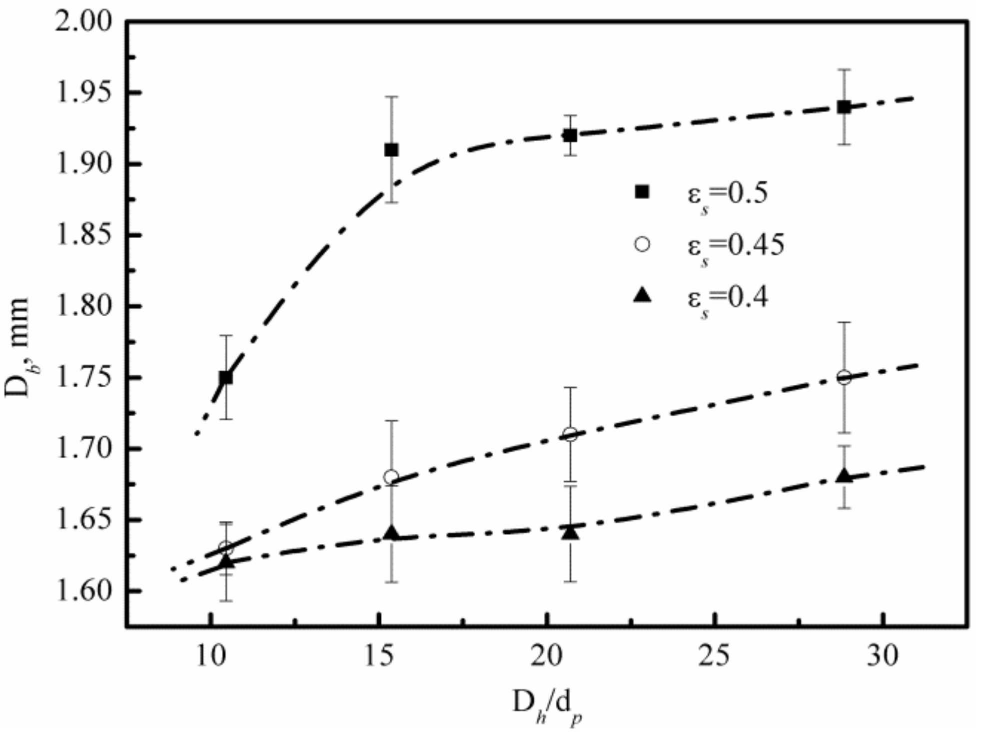
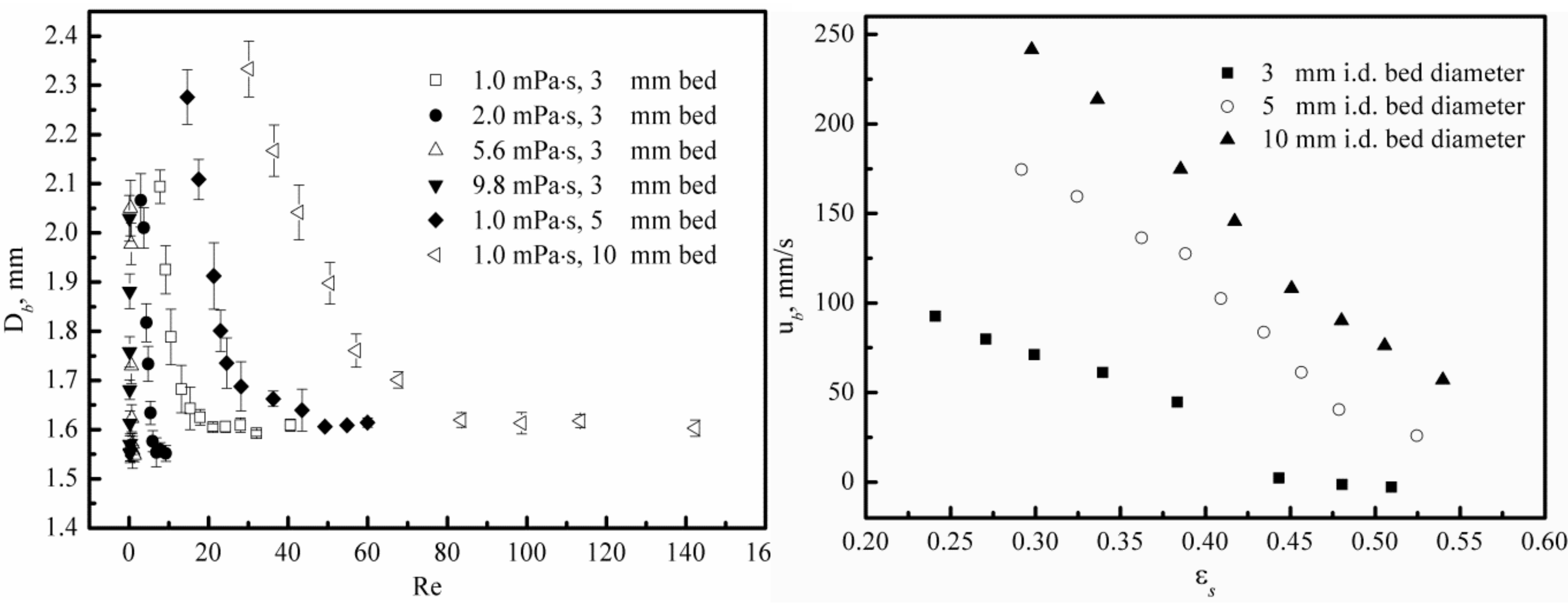


Figure 5. Effect of solid particles size on bubble diameter at various solid holdups in the mini-fluidized beds.

3. Results and Discussion

3.1 Hydrodynamics

3.1.4 Single bubble behavior in gas-liquid-solid micro-fluidized beds.



(a) **(b)**

Figure 6. Relationship between the bubble size and Re at different viscosity and bed diameter (a). u_g=0.034 m/s, ρ_p=2500 kg·m^{-3}, d_p=195 µm, D_h=3, 5, 10 mm, D_o=0.16 mm, H_s=9 mm and the bubble velocity with solid holdup and bed diameter (b). U_l=1.22-10.8 mm/s, u_g=0.034 m/s, ρ_p=2500 kg·m^{-3}, d_p=287 µm, D_o=0.16 mm

3. Results and Discussion

3.2 Numerical simulations

- Single bubble behavior in the 3 mm rectangular gas-liquid-solid mini-fluidized beds using DEM-VOF method with 90 μm solid particles was simulated.

Governing equations of fluid phase in the viscous laminar flow

$$\frac{\partial(\varepsilon)}{\partial t}+\nabla(\varepsilon \boldsymbol{u})=0$$

$$\frac{\partial(\varepsilon\rho_{\mathrm{f}}\boldsymbol{u})}{\partial t}+\nabla\left(\varepsilon\rho_{\mathrm{f}}\boldsymbol{uu}\right)-\nabla\varepsilon\tau=-\varepsilon\left(\nabla p_{\mathrm{rgh}}+\left(\boldsymbol{g}\cdot\boldsymbol{h}\right)\nabla\rho_{\mathrm{f}}-\boldsymbol{F}_{\sigma}\right)-\boldsymbol{F}_{\mathrm{fp}}$$

Transport equation for gas-liquid interface

$$\frac{\partial(\alpha)}{\partial t}+\nabla(\alpha \boldsymbol{u})=0$$

Motions equations of solid particles

$$m_{\mathrm{p}}\frac{\mathrm{d}\boldsymbol{v}_{\mathrm{i}}}{\mathrm{d}t}=\sum_{\mathrm{j}}\boldsymbol{F}_{\mathrm{c,ij}}+m_{\mathrm{p}}\boldsymbol{g}+\boldsymbol{F}_{\mathrm{pf}}$$

$$I_{\mathrm{p}}\frac{\mathrm{d}\boldsymbol{\omega}_{\mathrm{i}}}{\mathrm{d}t}=\sum_{\mathrm{j}}\boldsymbol{T}_{\mathrm{c,ij}}$$

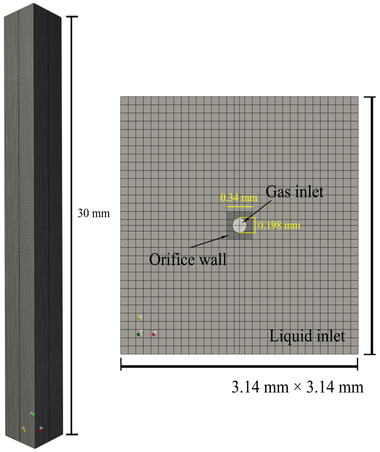


Table 1. Time steps and particle properties in numerical simulation.

Parameters	Value
Particle time step, Δt_{p}	5×10^{-5} s
Fluid time step, Δt_{f}	5×10^{-7} s
coupling interval, n_{c}	100
Particle number, n_{p}	155,000
Particle diameter, d_{p}	90 μm
Particle density, ρ_{s}	2500 kg/m^3
Young's modulus, E	5×10^{6} Pa
Poisson's ratio, η	0.45
Restitution coefficient, e	0.9
Friction coefficient, f	0.3

Figure 7. Computational domain size and grid geometry.

3. Results and Discussion

3.2 Numerical simulations

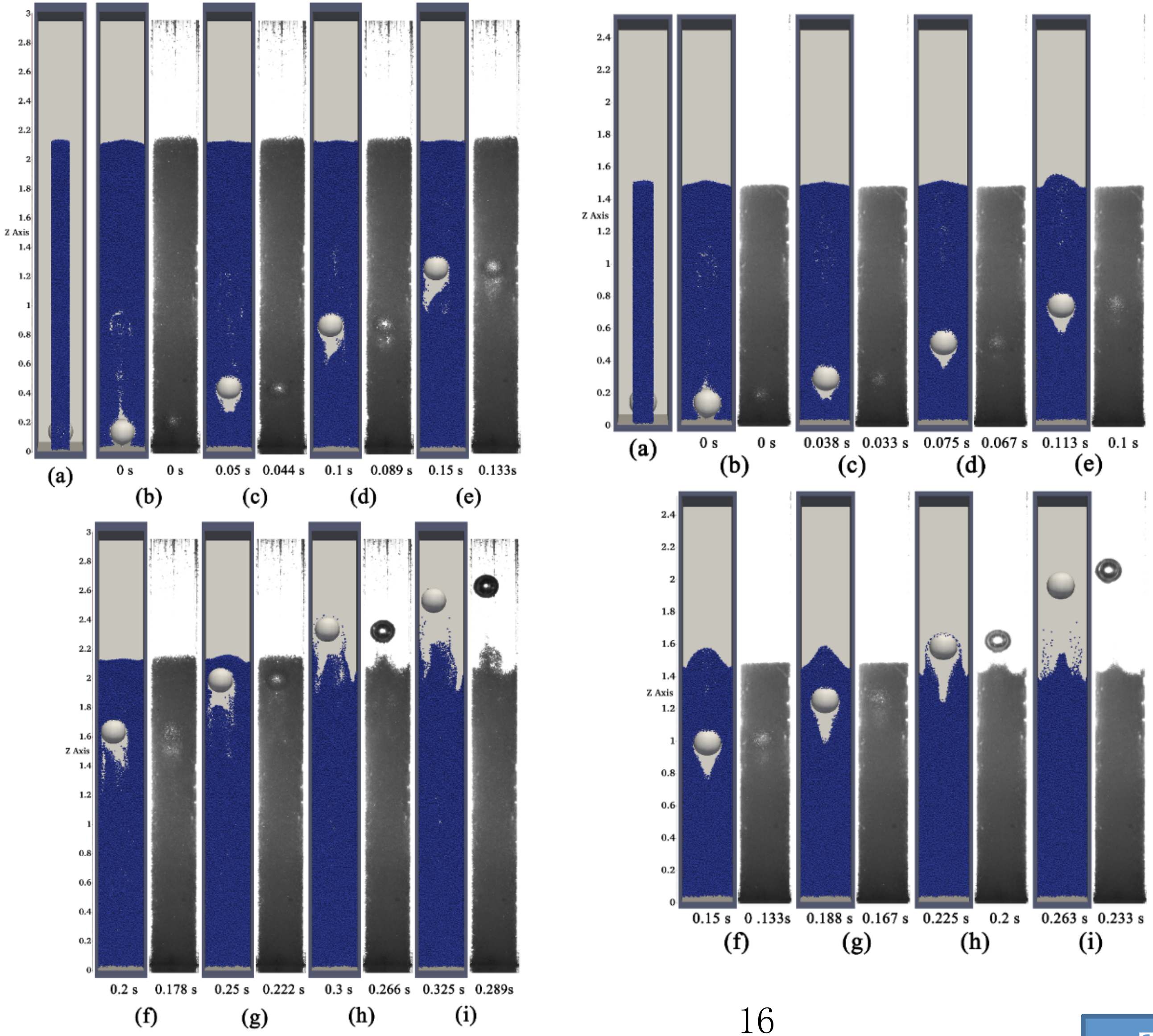


Figure 8. Experimental validation on the simulation of single bubble behavior in the gas-liquid-solid mini-fluidized bed with a low (left) and high (right) solid holdup.

4. Concluding Remarks

- Experiments on hydrodynamics in the gas-liquid-solid micro-fluidized beds were carried out and the data were analyzed.
- VOF-DEM method was used to simulate a rectangular 3.0 diameter liquid-solid mini-fluidized bed and the single bubble behavior in the mini-fluidized bed, and single bubble behavior was analyzed.
- Multi-phase flow mass and heat transfer will be considered in the further work.

Acknowledgments

- National Natural Science Foundation of China (Contract No.21376168; 91434204).

- Many thanks for my group members, especially as

  Dr. Li Yanjun and Li Xiangnan.

  M.E: Tang Can, Yang Zhongguo, Wang Xiaoyun, Dong Tingting and Yao Dong.

  Doctoral student: Li Chen

天津大學
Tianjin University

Thank you !