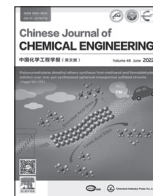




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Full Length Article

The motion mechanism and characteristic of bubble in a pseudo-2D tapered fluidized bed

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ABSTRACT

The different carbon nanotube (CNT) particles ([®]A and [®]V) were bed materials in the pseudo-2D tapered fluidized bed (TFB) with/without a distributor. A detailed investigation of the motion mechanism of bubbles was carried out. The high-speed photography and image analysis techniques were used to study bubble characteristic and mixing behavior in the tapered angle of TFB without a distributor. The fractal analysis method was used to analyze the degree of particles movement. Results showed that an S-shaped motion trajectory of bubbles was captured in the bed of [®]V particles. The population of observational bubbles in the bed of [®]V particles was more than that of [®]A particles, and the bubble size was smaller in the bed of [®]V particles than that of [®]A particles. The motion mechanism of bubbles had been shown to be related to bed materials and initial bed height in terms of analysis and comparison of bubble diameter, bubble aspect ratio and bubble shape factor. Importantly, compared to the TFB with a distributor, the TFB without a distributor had been proved to be beneficial to the CNT fluidization according to the study of bubble characteristic and the degree of the particle movement. Additionally, it was found that the mixing behavior of [®]V particles was better than [®]A particles in the tapered angle of TFB without a distributor.

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1. Introduction

The tapered fluidized bed (TFB) exhibits unique hydrodynamic characteristics due to the inverted taper and different regions exhibiting diverse fluidized degrees [1–4]. Compared with the cylindrical fluidized bed (CFB), the TFB is characterized by the capability of handling particles with different sizes and properties, as well as to exothermic reactions [2–5]. Therefore, it has been widely applied in many industrial processes such as immobilized biofilm reaction, incineration of waste materials, coating nuclear fuel particles, coal gasification and liquefaction, crystallization and roasting sulfide ores [2,4,6–9].

The TFB with/without a distributor has also been developed and widely used in the carbon nanotube (CNT) industrialization as a key component [4,10,11]. The literature is abundant with the preparation of CNT in the past three decades. Various studies, such

as hydrodynamics, mixing characteristics, reaction kinetics, morphology, characteristics of different growth process of CNT, the influence of catalyst size on CNT, the influence of operating parameters on CNT characteristics, have been reported [12–16]. Among them, it has been verified that the agglomerate–bubbling–fluidization (ABF) characteristics exist in the process of CNT preparation and fluidization [13,17]. Bubble has advantageous effects on the gas–solid mixing and gas circulation. Thus, it plays an important role in the process of CNT growth in the TFB. Additionally, the fluidization quality of particles is highly dependent on the distribution and characteristics of bubbles in the bed. Ideally, in order to achieve good fluidization quality, the number of bubbles in the bed should be large but the bubbles should be small in size, and they should homogeneously occupy the bed [18]. It is believed that a thorough exploration of bubble behavior during CNT fluidization is beneficial to the scale-up and rational operation of the TFB. In hydrodynamics research, the previous researchers have investigated the flow parameters in fluidization mechanism, such as minimum fluidization velocity, bed pressure drop, voidage distribution, solid holdup and solid velocity distribution, the effects

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of taper angle and gas distributor, bubble behavior, the formation mechanism and characteristic of bubbles [1–8,18–20]. In many of these studies, however, the motion mechanism and characteristic of bubbles during the CNT fluidization in the TFB with/without a distributor remain lacking, especially the mixing behavior of bubbles in taper angle of the TFB without a distributor. Hence, in order to supplement this gap, the bubble characteristics during the CNT fluidization in the TFB are studied in detail.

Different techniques have been developed to study the motion mechanism and characteristics of bubbles, which can be broadly classified into two categories: (i) intrusive techniques, which are named based on resistance, inductance, impedance, piezoelectric or thermal probes, and (ii) non-intrusive techniques, some of which are based on photographic, X-ray, light scattering and laser techniques [18]. Among them, a number of review papers have been published focusing on the non-intrusive techniques—image processing technology used in fluidized beds [18,21–23]. The development of image processing technology has paved the way for the use of this technique in hydrodynamic studies, which is viewed as a quick and convenient method, especially the analysis of bubble motion and characteristics. The greatest advantage of image processing techniques is that can obtain flow information through a high-speed camera in fluidized bed and be seen in high resolution and measured at the same time without disturbing the flow. Then it can be applied to analyze the data of large number of experiments. Therefore, in order to obtain the motion mechanism and characteristics of bubbles during CNT fluidization, we use image processing technology to obtain bubble motion information. Additionally, the fractal analysis is used to describe the degree of particle movement.

In the gas–solid systems, image processing technology has been widely used to analyze bubble characteristics, gas–solid mixing behavior, and velocity spatial distribution of particle in fluidized bed [18,21–26]. For instance, Busciglio *et al.* [18] developed a digital image analysis technique (DIAT) to analyze the bubbling characteristics (e.g. bubble diameter distribution, bubble aspect ratio, bubble velocity distribution), and confirmed the large potential of the technique developed by them. Wang *et al.* [23] used the image analysis techniques to study bubble behavior in terms of changes in velocity and aspect ratio, and found that the overall velocity of bubbles was directly correlated to its aspect ratio and inversely correlated to its particle coverage, while the acceleration and the aspect ratio and its change were inversely correlated. Zhu [24] studied the mixing behavior in a pipe fluidized bed using imaging processing, and demonstrated this technique had an ability to investigate the gas–solid mixing characteristics of bubble. Santana *et al.* [26] observed the bubble ejection mechanism by particle image velocimetry, the results showed that initial velocities in

the combined layer were higher than those of the particles in the nose of the leading bubble. Additionally, Akiyama *et al.* [27] used a box-counting method to calculate the fractal dimension, and showed that the quantitative information was given for the degree of gas–solid mixing by fractal dimension. Other scholars had also made some related research to exhibit the gas–solid mixing characteristic, such as the size distribution [28], the degree of surface irregularity [29], and aggregation analysis [30]. Thus, the image processing and fractal analysis can be used as a group of very superior methods for analyzing the motion mechanism and characteristics of bubble in the TFB.

In the present work, imaging processing technique is used to study the motion mechanism and characteristic of bubbles during the CNT fluidization in the TFB with/without a distributor, and make detailed comparisons. Then, we used fractal dimension to analyze the degree of particle movement, data which are used to verify the better fluidization quality in the TFB without a distributor.

2. Experimental

2.1. Materials

The agglomerated multi-walled CNT ([®]A) and vertical array multi-walled CNT ([®]V), which are used as the bed materials. The physical properties of MWCNTs are summarized in Table 1 [4]. The morphology of MWCNTs at different scales are shown in Fig. 1. And the [®]A and [®]V with nanoscale diameter and micro-scale length prefer to aggregate into multi-scale agglomerates (MSA) [4]. The mass of MWCNTs used in different bed heights in the experiment are shown in Table 2.

Table 2
The mass of MWCNTs ([®]A and [®]V)

Bed material	With/without a distributor (N/Y)	Initial bed heights <i>H</i> /cm	Mass/g
[®] A particles	N	20	11.800
	N	30	28.600
	N	40	68.760
[®] V particles	N	20	4.385
	N	30	10.678
	N	40	19.520
[®] V particles	Y	10	6.365
	Y	15	9.547
	Y	20	12.730

Table 1
Physical properties of MWCNTs ([®]A and [®]V)

Bed material	Bulk density $\rho_b/\text{kg}\cdot\text{m}^{-3}$	Particle density $\rho_p/\text{kg}\cdot\text{m}^{-3}$	True density $\rho_t/\text{kg}\cdot\text{m}^{-3}$	Particle size range/mm	Particle mean size d_p/mm
[®] A particles	132	150.22	193.9	0.15–0.80	0.48
[®] V particles	37	57.35	77.3	0.15–1.25	0.70

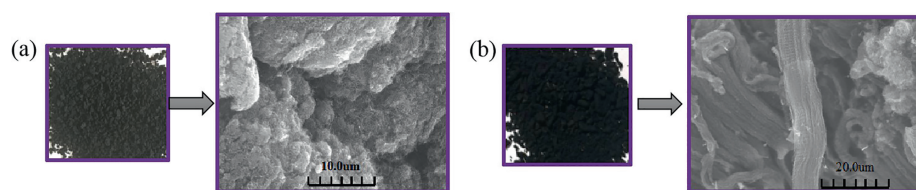


Fig. 1. Morphology of MWCNTs; (a) agglomerated MWCNT ([®]A), (b) vertical array MWCNT ([®]V).

2.2. Setup

Pseudo two-dimensional (pseudo-2D) bed is crucial for the understanding of the dynamics of gas-particle systems, especially the characteristic and motion mechanisms of bubbles [18,22–24,26,27]. Pseudo-2D fluidized bed typically has transparent walls in order to allow optical access to the bed, which aims to understand the motion mechanisms of bubbles in the bed. Fig. 2 shows a schematic of the experimental facility used in this work, which mainly includes a pseudo-2D cold TFB, image acquisition unit, and illuminating system. The experiment is performed at room temperature and ambient pressure. The gas flow, as shown in Fig. 2(b), is injected from the side wall of tapered section into the TFB with/without a distributor and via a vertical down nozzle. The inner diameter of the vertical down nozzle of the inlet tube is 8 mm. In addition, a porous gas distributor is adopted and has a thickness of 5 mm, the hole diameter of 4 mm, and the opening fraction of 36.8%. The pseudo-2D bed of vessel dimensions 0.1 m $\times$ 1.86 m $\times$ 0.02 m (width, height, and thickness). The image acquisition unit consists of a high-speed camera and a computer. The high-speed camera (Fastcam Mini ux100) is used to capture the fluidization process of CNT and bubble behavior. Simultaneously,

the aperture of the camera is adjusted to a maximum of $f/2.8$, and the exposure time is calibrated to 2000 μs . The high-speed camera is fixed on a tripod and oriented to the front wall of the TFB. It is located 1 m in front of the TFB, and adjusted to a height of 0.6 m. The images are recorded with image size of 1280 $\times$ 1024 pixels. As shown in Fig. 2(a), the illuminating system consists of four 160 W DC LED lights (no flicker), which are placed symmetrically on the back and side of the fluidized bed, respectively.

2.3. Methodology

2.3.1. Image processing methods

In this study, the fluidization process of CNT is captured using a high-speed camera. As shown in Fig. 3, the image data is extracted from sequence frames, and the selected images are processed using MATLAB R2016a through the developed algorithm. The detailed steps of image processing have been reported in our previous work [31]. The simple steps are listed below.

- (1) Image loading: The captured images are loaded in the MATLAB software.

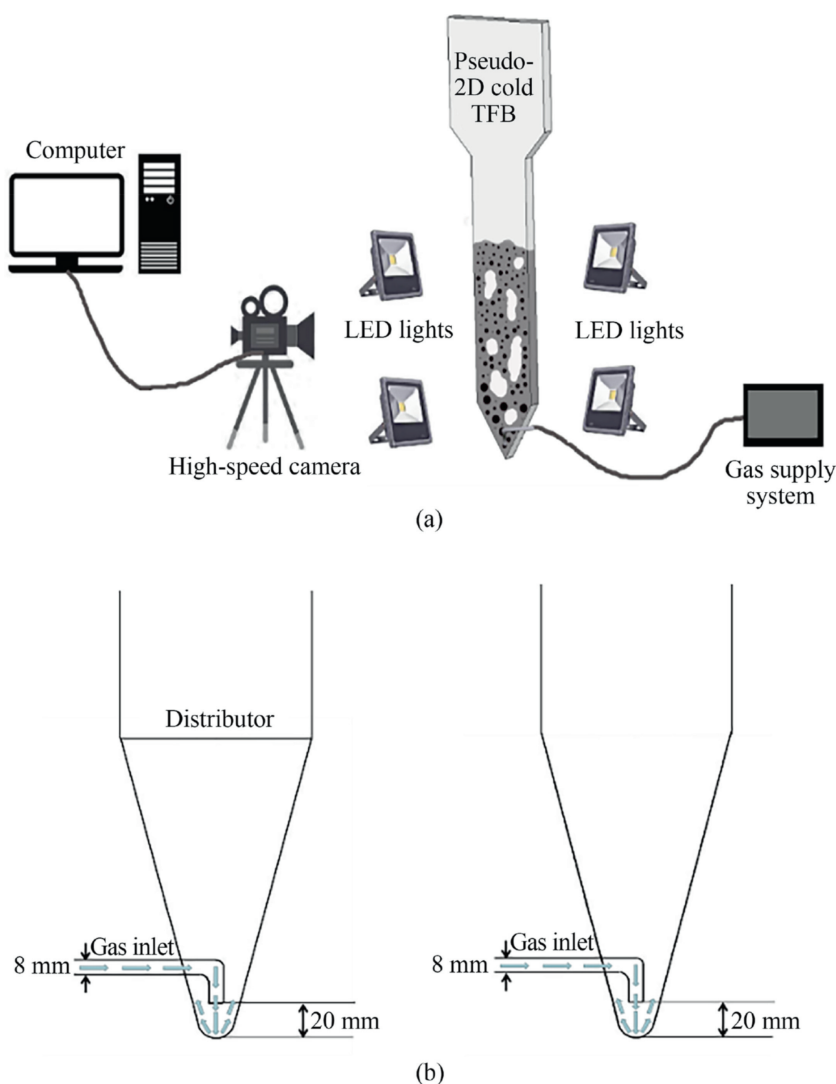


Fig. 2. (a) The schematic of the experimental facility. (b) The sketch pictures of the TFB with/without a distributor.

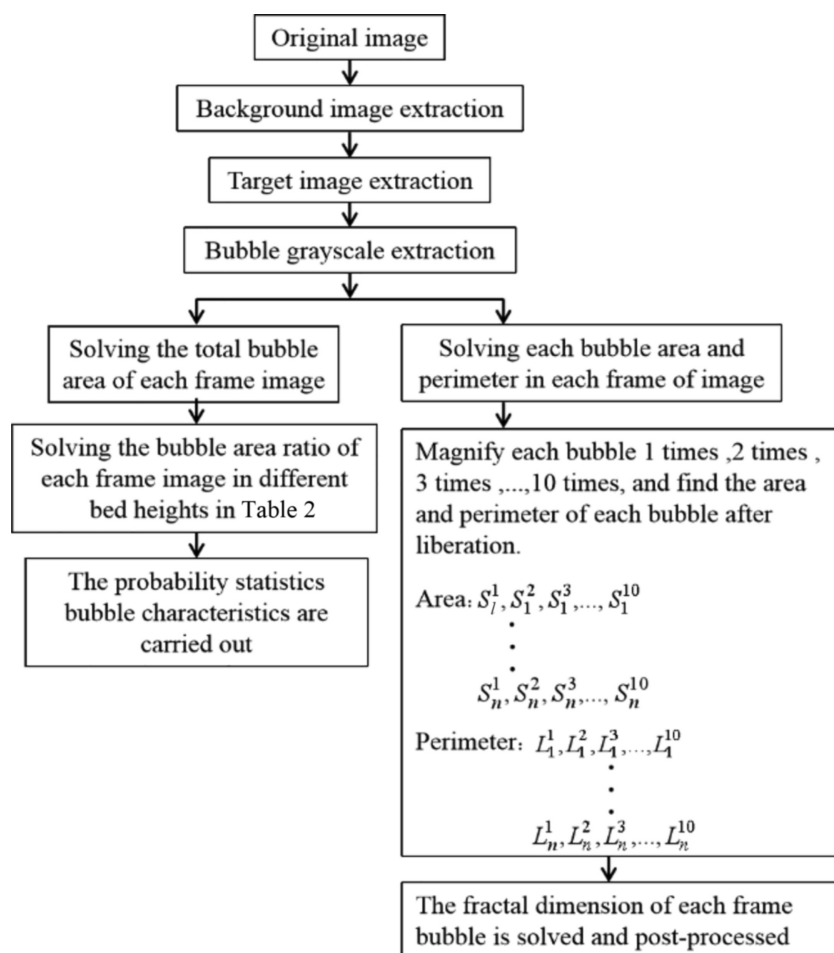


Fig. 3. Flow chart of image processing.

- (2) Image cropping: Images are cropped to remove the excess region [32]. Moreover, in order to keep the inner diameter border consistent with the image boundary, the unexpected pixels outside the inner diameter boundary are eliminated.
- (3) Background subtraction: To capture a background image which does not include any moving target image.

- (4) Image segmentation: The thresholding method as the most simple and common technique is widely used in separating the target and background images. The original image is carried out to conduct the grayscale statistics and find the best threshold value, then grayscale image (*i.e.*, any pixel assumes values ranging from 0 to 1 in Fig. 4) is separated

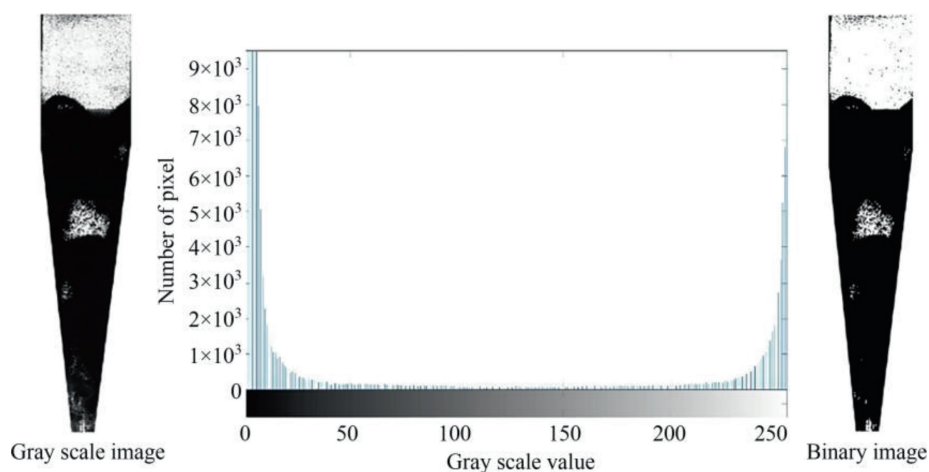


Fig. 4. The selection of the best threshold value and image binarization.

by the best threshold value. The grayscale histogram of pixel intensity, such as the one shown in Fig. 4. The image segmentation process can be done easily by selecting the appropriate threshold value (T). This can be accomplished by the following expression, relating the grayscale image $I(x,y)$ to the binary image $g(x,y)$, as shown in Fig. 4.

$$g(x,y) = \begin{cases} 1 & I(x,y) \geq T \\ 0 & I(x,y) < T \end{cases} \quad (1)$$

The pixels value equals 1 are identified as bubble phase pixels, while the others are identified as emulsion or dense phase.

- (5) Filtering of false bubbles and other peripheral voids: The bubbles which are followed by many small bubbles at the same velocity, the rising voids adherent to the lateral walls, and bubbles bursting at the top of the bed are carefully neglected in this work [18].

2.3.2. Bubble parameters calculation

The bubble aspect ratio (AR), a parameter that reflects the dynamic behavior of rising bubbles, is defined as Eq. (2) [22,33]:

$$AR = d_y/d_x \quad (2)$$

where d_y and d_x are the maximum vertical and horizontal dimensions of the bubble.

The bubble shape factor (SF) is defined as Eqs. (3) and (4) [22,33]:

$$SF = \pi d_b/L \quad (3)$$

$$d_b = \sqrt{\frac{4S}{\pi}} \quad (4)$$

where d_b is an area-equivalent diameter, L is the bubble perimeter, and S is the bubble area.

The SIM is known as the slit-island technique or the area-perimeter method [34,35]. The perimeter L and area S of regular figure in Euclidean geometry are as Eq. (5):

$$L \propto S^{1/2} \quad (5)$$

For irregular patterns such as islands in nature and microstructures in materials, the relationship between them is as Eq. (6):

$$L^{1/D_f} \propto S^{1/2} \quad (6)$$

D_f is the fractal dimension (FD).

3. Results and Discussion

3.1. The motion mechanism of bubble

In order to understand and explain the motion mechanism of bubbles, the two aspects are carried out: the motion trajectory of bubbles and changes of bubble size in the process of particle rising or falling in the bed. As shown in Fig. 5, it is observed in the experiment that bubbles form above the distributor, and some bubbles may coalesce to form larger size bubbles at intermediate heights, while others may completely collapse and vanish or divide a big size bubble into smaller ones further up such as the red box marked in Fig. 5(a)–(e) in the TFB with a distributor. In other words, when the bubbles travel upward through the bed at a steady gas velocity, they go through a process from small to large and then to small during the motion of the whole bed. Meanwhile, as shown in Fig. 5(f), (a) similar S-shaped motion

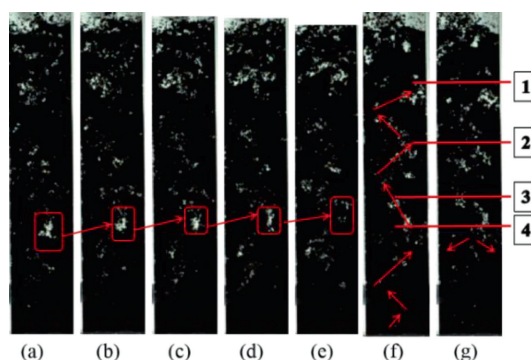


Fig. 5. The movement process of the ^{60}V particles in the TFB with a distributor.

trajectory of bubbles is captured. The flow pattern of bubbles agrees with the observations from the reports of other researchers [36–38]. Additionally, when the particles fall back to the bed after they erupt on the surface of the bed, some bubbles form the falling region in the bed, as shown in Fig. 5(g). In order to see the movement process of bubbles, four contrast lines of bubbles movement are added between Fig. 5(f) and (g). It is easy to see that the bubbles in Fig. 5(g) is in a falling state compared to the bubbles in Fig. 5(f). The reason is that a circulating flow of particles is caused by the bubble eruption and particles back to the bed in the bubbling fluidized bed [36]. Because the bed of particles tends to be compressed state at a constant gas velocity, there will be one or more falling regions of particles. As a result, the bubbles also follow the motion of particles, and one or more falling regions appear in the bed. Moreover, the falling region generally occurs where the particles are most blocked in their upward movement.

As shown in the red box of Fig. 6(a)–(e), in the TFB without a distributor, the bubble size changes from large to small and then to large in the ascent process of particles in a series of images, which is similar with the phenomenon in the TFB with a distributor. That is, the bubbles undergo the process of combination, division, disappearance and recombination in the rising process. The first combination occurs above the nozzle at the taper angle (the bubbles are elongated); after that, due to the resistance of particles in the bed during the upward movement of gas velocity, the emulsion phase in the bed is gradually filled with particles, and the bubbles are divided or disappeared (the bubbles are compressed). When the bubbles are close to the upper surface of the bed, the

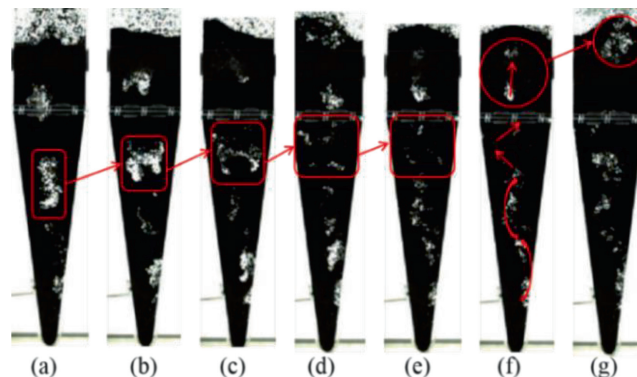


Fig. 6. The movement process of the ^{60}V particles in the TFB without a distributor.

resistance of particles is less than the buoyancy, and the small size bubbles coalesce along the rising channel to form large size bubbles (bubbles coalescence and elongation). Obviously, as the red box indicated in Fig. 6(f)–(g), the motion trajectory of the bubble follows an S-shape and then a straight line, and the bubbles rise vertically along the central channel of the bed and erupt on the surface of the bed. As shown in the red box of Fig. 7(a)–(e), during the rising of bubbles, the whole bed seems to be moved upward by a large size bubble supporting the bed. Since the upward buoyancy of the particles is less than the resistance of particles, the falling particles are mixed with the bubble phase to form the emulsion phase. Thus, a large size bubble is divided into the small size bubbles. When the bubbles are about to reach the surface of the bed, many bubbles coalesce to form large vertical rising bubbles, which burst on the surface of the bed and drive the particles to erupt upward. Additionally, in the bed of $^{\circ}\text{A}$ particles, no regular trajectory of bubble movement is found, which may be related to the properties of the particles. The spherical degree of $^{\circ}\text{A}$ particles is higher than $^{\circ}\text{V}$ particles [4], the friction force between particles and wall and between particles is less than that of $^{\circ}\text{V}$ particles. Moreover, $^{\circ}\text{A}$ particles are heavier than $^{\circ}\text{V}$ particles. They have higher particle density, higher mass and dense bed. As a result, in the process of $^{\circ}\text{A}$ particle rising with gas velocity, the bubble boundary is obvious in the bed, the small bubbles are not easy to disperse, and tend to gather into clusters of large bubbles shown in Fig. 7(a)–(e). However, in the process of small bubbles moving and aggregating into large bubbles, several small bubbles approach each other at the same time along with the direction of gas velocity, and the following particles quickly enter the emulsion phase around the bubble phase, and finally fall back to the particle phase in the bed. The bubble phase continues to move upward with the direction of gas velocity and participates in the movement behavior of the next small bubble cluster. Therefore, the monolithic bubbles cluster move upward in a straight line, but the trajectories of individual bubbles do not form a regular pattern.

As shown in Figs. 5–7, typical bubbles are not spherical but have a flattish or curving profile. The region just below the bubble is the wake region. The particles in a wake are carried along with the bubbles for a distance, especially in the bed of $^{\circ}\text{A}$ particles [36,39]. In the bed of $^{\circ}\text{V}$ particles, the flow pattern of bubbles is similar, but the observational bubble size is larger in the TFB without a distributor than that in the TFB with a distributor due to the presence of the distributor. The distributor produces mostly small size bubbles. In the TFB without a distributor, due to the different properties of particles, the population of observational bubbles in

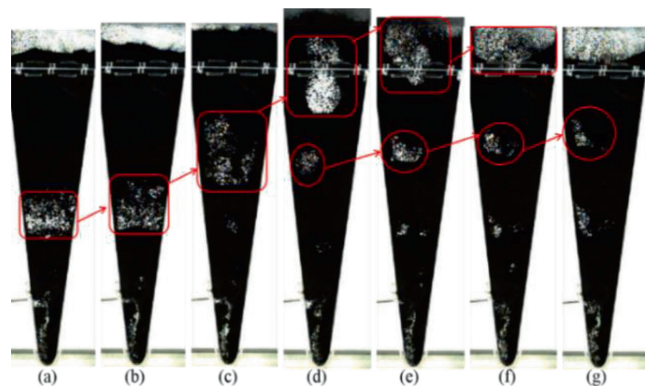


Fig. 7. The movement process of the $^{\circ}\text{A}$ particles in the TFB without a distributor.

the bed of $^{\circ}\text{V}$ particles is more than that in the bed of $^{\circ}\text{A}$ particles, and the bubble size is smaller in the bed of $^{\circ}\text{V}$ particles than that in the bed of $^{\circ}\text{A}$ particles. The relevant bubble characteristics will be quantitatively analyzed below. In conclusion, it can be seen that the motion trajectory and size of bubbles vary greatly with bed materials and bed structure.

3.2. Bubble characteristics

3.2.1. Comparison of bubble diameter distribution

Bubble diameter distribution is an important parameter of the bubble dynamic behavior in a bed. It quantitatively reflects the coalescence and/or break-up phenomena of bubble occurring in the TFB. Figs. 8–10 report the probability density distribution of experimental bubble diameter recorded in different bed heights and materials. It can be easily observed that the experimental data shows a skewed distribution with one single peak, which is consistent with previous report [18,40]. However, the difference is that they study the bubble diameter of distribution at different elevations from the distributor in the fluidized bed. Meanwhile, an aim of this study is to obtain the bubble diameter distribution throughout the bed at different initial bed heights and superficial gas velocities to study the bubble dynamic behavior in the TFB with/without a distributor, so that the operation parameters, which are conducive to CNT fluidization, can be better grasped.

The bubble diameter distribution of $^{\circ}\text{V}$ particles is concentrated in 2–2.5 cm and 2–3 cm in the TFB with/without a distributor, respectively. The bubble diameter distribution of $^{\circ}\text{A}$ particles is concentrated in 2–3.5 cm in the TFB without a distributor. The results indicate that the largest bubble diameter size appears in the $^{\circ}\text{A}$ particles. Meanwhile, it is also verified that the bubble diameter size is related to bed material, which is consistent with the above analysis of motion mechanism. As shown in Fig. 8, at the same initial bed height, the probability density value of bubble diameter becomes small with the increase of gas velocity. It shows that at the same bed height, the higher the gas velocity is, the more bubbles are coalescent and/or broken. At the same gas velocity, as the initial bed height increases, the probability density value of bubbles with a diameter of 2–2.5 cm increases. This result indicates that the higher the bed is, the coalescence and/or breakage rate is lower at the same gas velocity. The changes of bubble diameter distribution of the $^{\circ}\text{V}$ particles in the TFB with a distributor are similar to that in the TFB without a distributor. But the probability density value of bubbles with a diameter of 2–3 cm decreases with the increase of initial bed height. It indicates that the higher the bed is, the more the coalescence and/or breakage rate is. Another indication of the result is that the phenomenon is beneficial to the fluidization of particles and the heat and mass transfer during the CNT growth, because the beds are constantly rising in the growth process of CNT. Similarly, at the same bed height, the higher the gas velocity of the $^{\circ}\text{A}$ particles is, the more bubbles are coalescent and/or broken in the TFB without a distributor. However, at the same gas velocity, the bubble diameter distribution has no obvious rule with the increase of bed, which is similar to the above observations of motion mechanism of $^{\circ}\text{A}$ particles. In a word, the above mentioned further indicates that bubble dynamic is related to bed materials and initial bed heights.

3.2.2. Comparison of bubble aspect ratio (AR) and shape factor (SF)

Aspect ratio (AR) and shape factor (SF) are important characteristics of a bubble because they strongly influence the hydrodynamics of the bubble and direct correspondence to the behavior of bubbles that dominate the overall state of the bed [21].

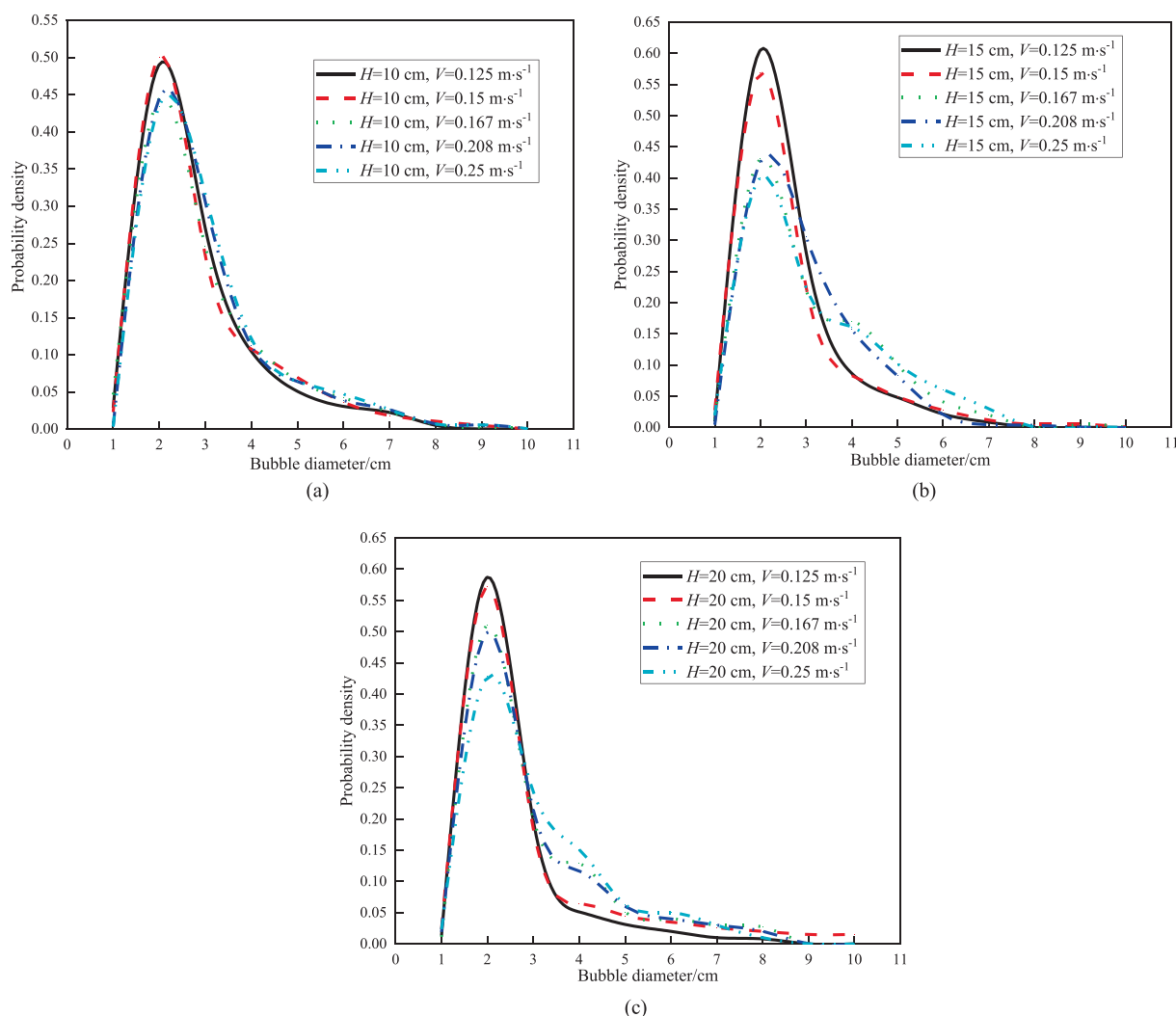


Fig. 8. The bubble diameter distribution of @V particles at different bed heights in the TFB with a distributor. (a) $H = 10 \text{ cm}$; (b) $H = 15 \text{ cm}$; (c) $H = 20 \text{ cm}$.

In Figs. 11–16, the probability density distribution of bubble AR and SF over superficial gas velocity are reported. Spherical bubbles are defined as $AR \sim 1$, and the ellipsoidal or asymmetrical bubbles are expressed as $AR < 1$ or $AR > 1$. As shown in Figs. 11–13, the number of the bubbles with $AR < 1$ and $AR = 1$ is far less than that with $AR > 1$, except in Fig. 11(c). This implies that vertically stretched and asymmetrical bubbles dominate the CNT fluidization. Two phenomena are captured in Fig. 11. On the one hand, at the same initial bed height, the AR increases with the increase of velocity, the highest value of single peak gradually shifts to the right, and the bubbles are obviously elongated; On the other hand, at the same gas velocity, the AR is less elongated than the former with the rise of initial bed height. It is worth noting that an approximately spherical bubbles appear at lower gas velocity in Fig. 11(c), which is related to the distributor and initial height of bed material. As shown in Fig. 12, at the same initial bed height, the peak of probability density of AR increases alternately, which indicates the bubbles are alternately elongated. However, the bubble elongation is more obvious than that in Fig. 11, which could be due to the role of tapered angle. The result is beneficial to increase the contact area between particles and bubbles in the tapered angle, which is beneficial for CNT preparation. Because the tapered angle region is the main reaction area where the CNT begins to

grow, there are few catalyst particles, and the larger the gas–solid contact area is, the more favorable the reaction is. Different from @V particles in the TFB without a distributor, the AR of @A particles has obvious changes. As shown in Fig. 13, with the increase of gas velocity, the lower the peak value of probability density distribution of AR is, the more uniform the degree of bubble is elongated, and a small part of the bubble is approximately spherical. The result verifies and shows the motion mechanism of @A particles in the TFB without a distributor. Furthermore, the bubbles are also significantly elongated with the increase of the bed at the same gas velocity. In short, all these quantitative analyses show the AR of bubble is closely related to bed materials and structure.

As shown in Figs. 14–16, a similar phenomenon is captured: at the same initial bed height, the probability density of bubble SF decreases and becomes well-distributed with the increase of gas velocity. The result indicates that the interaction between multiple bubbles in the whole bed gradually increases. Additionally, as shown in Fig. 14, at the same gas velocity, the probability density distributions of bubble SF shift to the right gradually, indicating that the interaction between multiple bubbles increases in the bed of @V particles. However, the probability density distributions of SF are no obvious changes in the TFB without a distributor, whether they are @V or @A particles. Moreover, the highest peaks

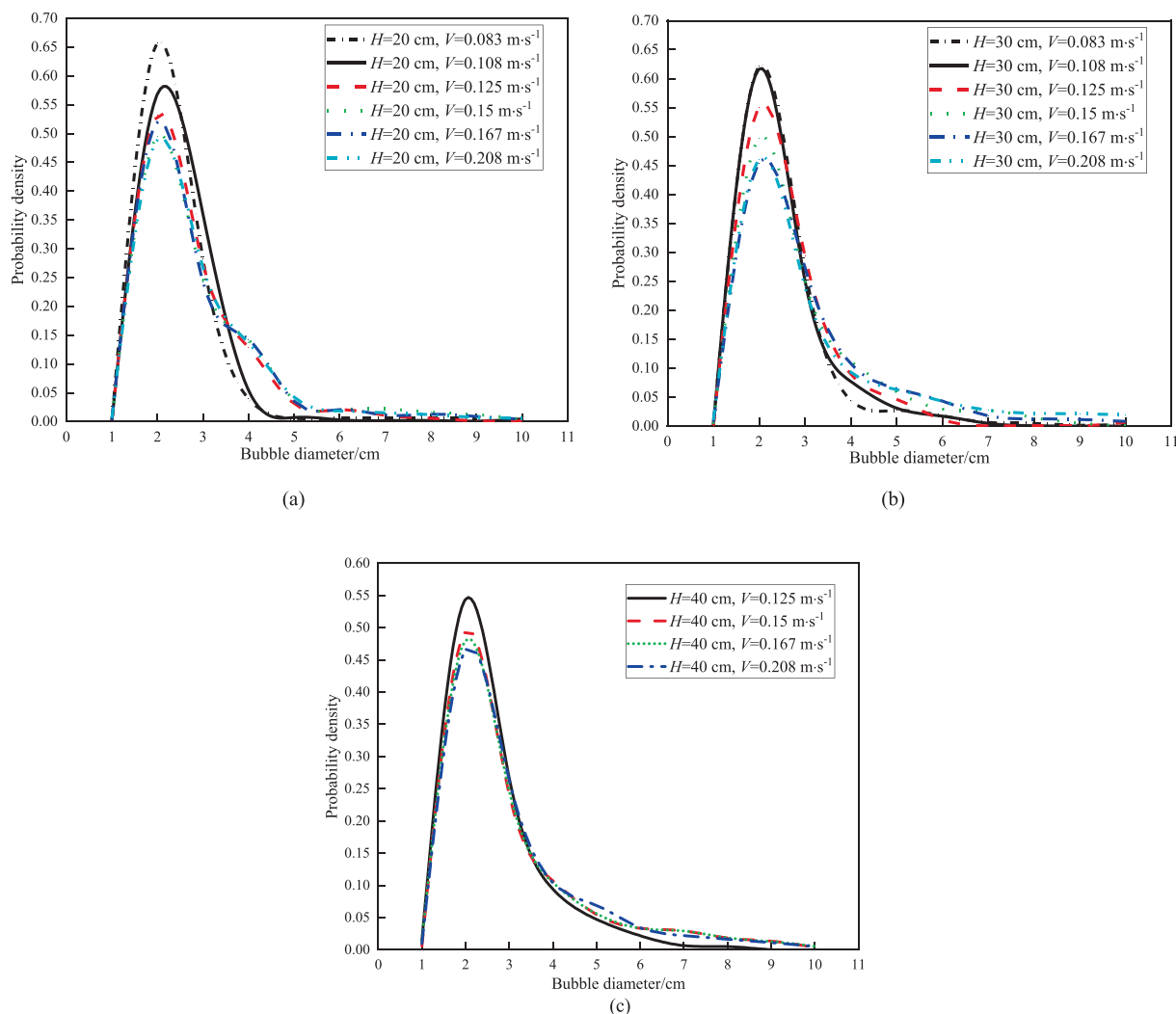


Fig. 9. The bubble diameter distribution of @V particles at different bed heights in the TFB without a distributor. (a) $H = 20$ cm; (b) $H = 30$ cm; (c) $H = 40$ cm.

of SF of bubbles in the bed of @V particles are between 0.15–0.2 in Fig. 15, and that of @A particles concentrate at 0.15 in Fig. 16, which indicates that the interaction between multiple bubbles in the bed of @A particles is weaker than that in the bed of @V particles. Consequently, bubble SF in the bed without a distributor has the characteristics of irregular and concentrated interaction between multiple bubbles. Importantly, the probability density distribution of bubble SF in different bed materials is similar.

3.3. The fractal dimension (FD) of bubble

The presence of bubbles provides the driving force of particle back mixing and “agitation” in the bed [20,41,42]. Thus, it is crucial to study how bubbles impact particle movement. The gas velocity distribution of bubble FD gives the quantitative information about movement degree of particles and gas–solid mixing. Generally, the bubble FD is used to characterize the degree of particle movement. The larger the bubble is, the larger the bubble FD is [43]. In the fluidization process of CNT, the higher the gas velocity is, the more bubbles in the bed are. The particles near the bubbles are moved and extruded. Fig. 17 shows the FD of a single bubble. According to Eqs. (5) and (6), the FD of the single bubble is 1.039. And this method is used to calculate the fractal dimension of all bubbles.

As shown in Fig. 18(a), the higher the initial bed height of @V is, the greater the average fractal dimension (AFD) is; and the higher the gas velocity is, the greater the AFD (*i.e.* degree of average movement of the particles) is. Therefore, whether the bed height rises or the gas velocity increases, the average movement of the particles increase in the bed, which will lead to the uneven motion of the particles in the TFB without a distributor. On the contrary, as shown in Fig. 18(b), the higher the initial bed height of @V is, the smaller the AFD is; the higher the gas velocity is, the smaller the AFD is; and the AFD gradually reduces to a platform. The result shows that, in the TFB without a distributor, the movement of particles becomes uniform and steady with the increase of initial bed height and gas velocity. In other words, over time of @V particles growth, the bed height rises, and the particles move more evenly. Compared to the result in Fig. 18(b), as the gas velocity increases, the AFD decreases first and then slowly rises to a platform in Fig. 19, which indicates the movement degree of @A particles decreases first and final stabilization. Overall, in the TFB without a distributor, the movement degree of the particles will not be decreased or increased alone, but then a platform will be reached to make the average particle movement stable in the bed. Compared to CNT fluidization in the TFB with a distributor, the phenomenon in the TFB without a distributor will be beneficial to the stable

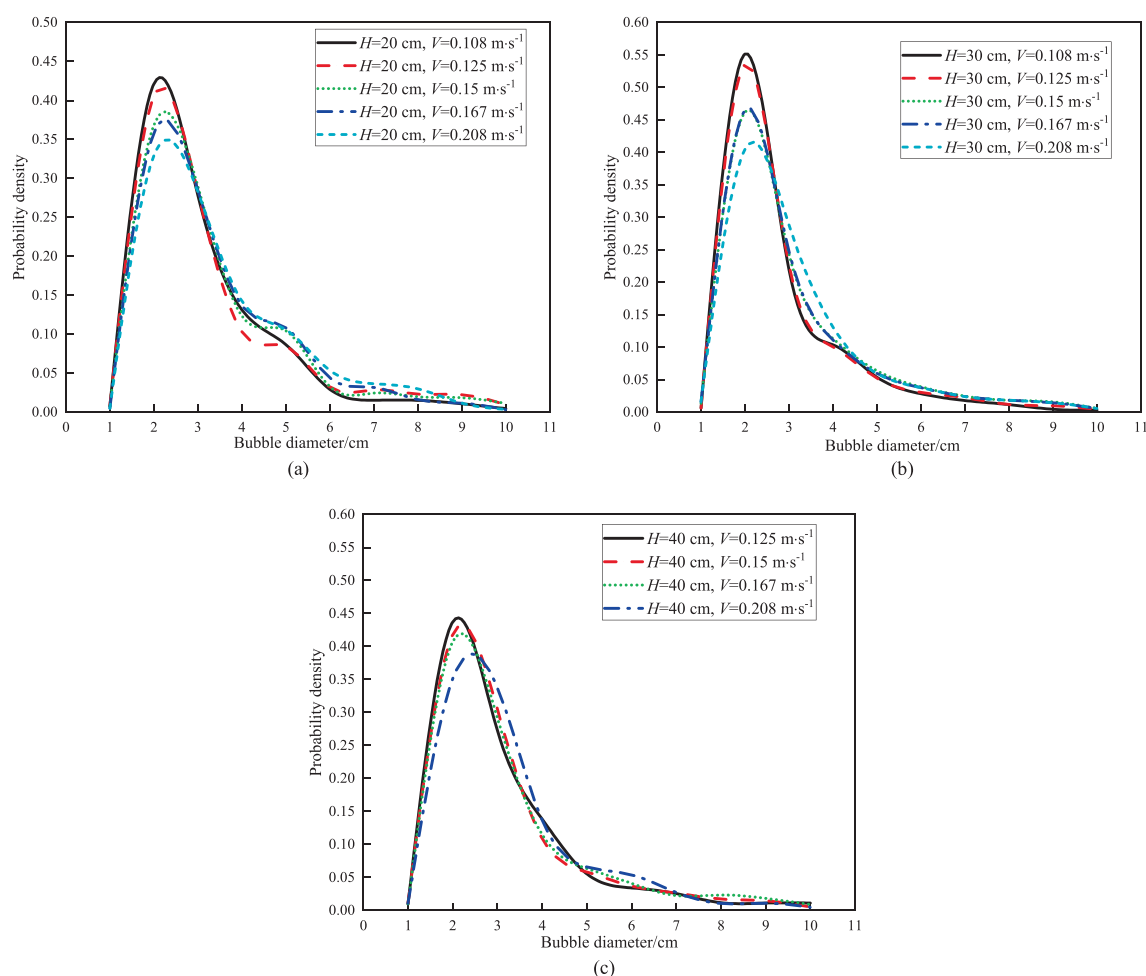


Fig. 10. The bubble diameter distribution of [®]A particles at different bed heights in the TFB without a distributor. (a) $H = 20$ cm; (b) $H = 30$ cm; (c) $H = 40$ cm.

fluidization of the CNT particles. This result is also verified that the CNT in the TFB without a distributor is more suitable for the fluidization.

Furthermore, combined with the above analysis of the bubble movement mechanism and characteristics, the higher the gas velocity is, the higher the bed is, the higher the bubble AR is, and the bubble is elongated (*i.e.* increase of the bubble perimeter). With the steady inflow of gas, the elongated large bubbles are dispersed into small bubbles, which continue to move upward in the bed and then become large bubbles. In this way, the coalescence and splitting of bubbles go round and round, and the AR and SF of bubbles are constantly changing. At the same gas velocity and the initial bed height, the number of bubbles in the [®]V particles bed is more than that in [®]A particle bed, and bubble size in [®]V particles bed is smaller than that in [®]A particle bed, which indicates that the degree of particle movement in [®]V particle bed is more intense than that in [®]A particle bed. Thus, the fractal dimension (FD) of particles in [®]V particle bed is larger than that in [®]A particle bed.

In addition, the weight of bed particles is similar in fluidized bed with a distributor (initial bed height is 15 mm) and without a distributor (initial bed height is 30 mm). There are more small bubbles near the distributor in fluidized bed, their perimeter and area are also smaller than that in fluidized bed without a distributor. However, due to the resistance caused by the distributor, the bubble average fractal dimension in the bed with a distributor is less than the one in the bed without a distributor, as shown in

Fig. 18. That is, the degree of average particle movement in the bed with a distributor is less than that in the bed without a distributor. Therefore, for the bed with/without a distributor, the fractal dimension of the bubble is related to the weight of the particles in the bed.

3.4. The mixing behavior of bubbles

It is important to explicitly investigate the mixing behavior of bubbles in a bed. Therefore, in order to further study the mixing characteristics in the tapered angle region of the TFB without a distributor, as shown in Fig. 20, we try to divide the tapered angle region into five axial domains and calculate the bubble volume fraction (BVF, *i.e.* the proportion of the bed occupied by bubbles) with the increase of gas velocity. The BVF in the tapered angle region is determined by the temporal development of bubbles throughout the region driven by factors such as flow intensity and the interaction of bubbles. The interaction and spatial distribution of bubbles are coupled and governed by the gas velocity [26]. As shown in Figs. 21 and 22, the BVF in each region varies with the gas velocity. Although there is no obvious regularity, the significant trend of the changes of BVF gets similarity. It is well known that the more BVF is, the more population of bubbles are, and the larger gas-CNT contact area is, the better mixing behavior is.

When the initial bed is 20 cm in Fig. 21(a), for [®]V particles, it is easy to see that there are the most bubbles at the top region

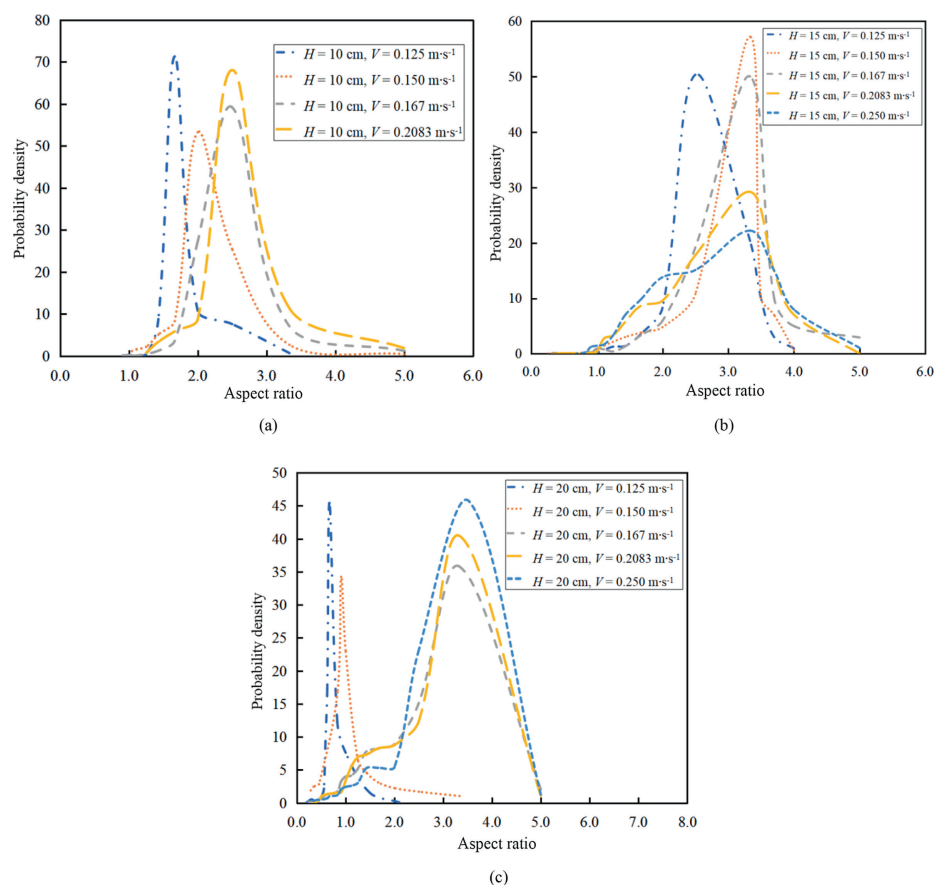


Fig. 11. The AR of @V particles at different bed heights in the TFB with a distributor. (a) $H = 10$ cm; (b) $H = 15$ cm; (c) $H = 20$ cm.

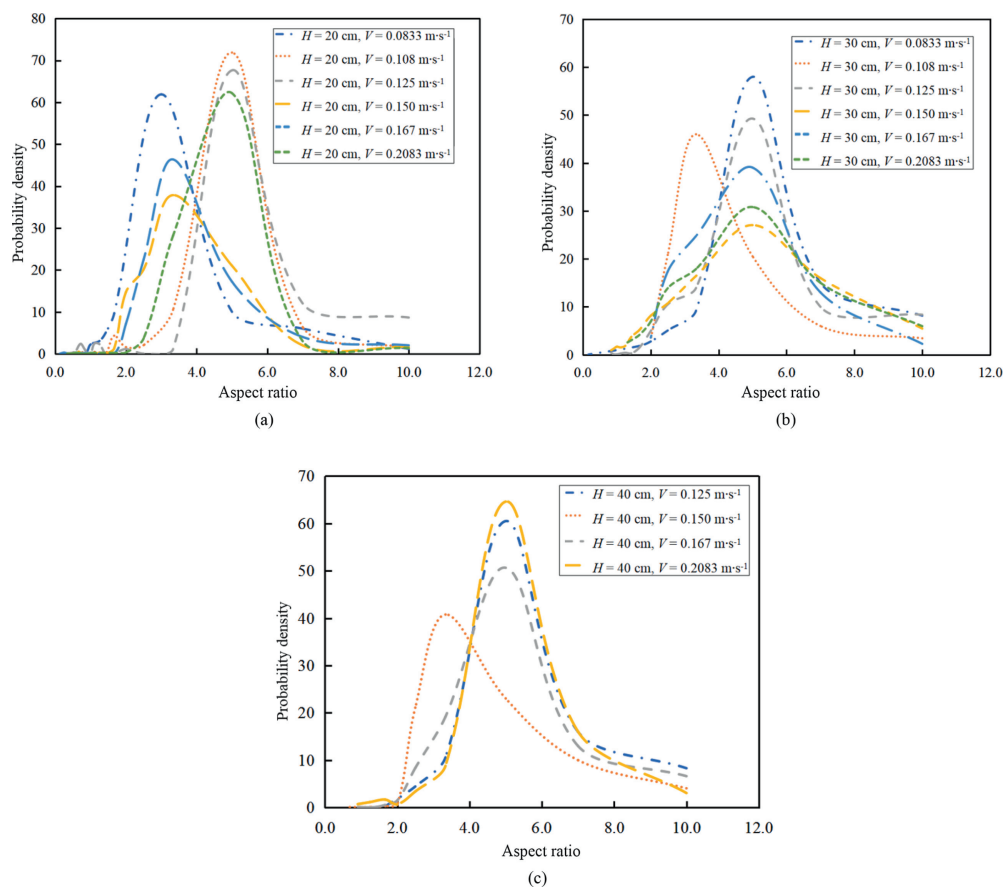


Fig. 12. The AR of @V particles at different bed heights in the TFB without a distributor. (a) $H = 20$ cm; (b) $H = 30$ cm; (c) $H = 40$ cm.

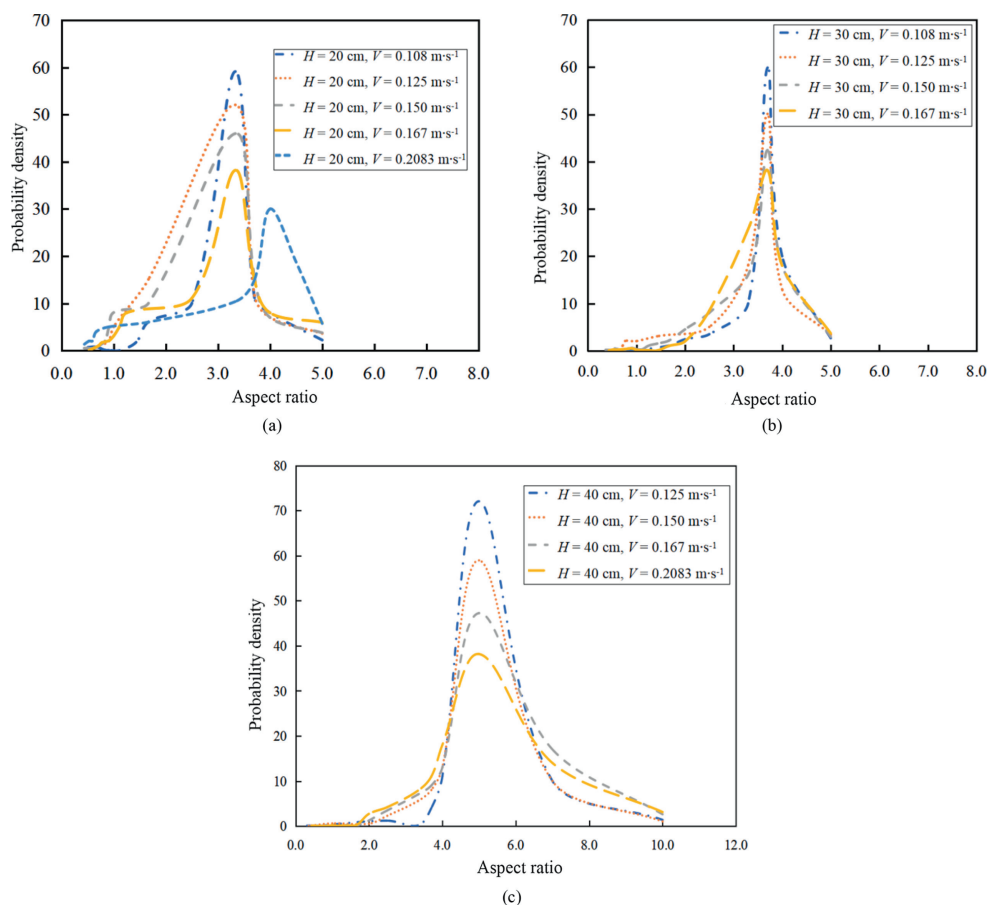


Fig. 13. The AR of @A particles at different bed heights in the TFB without a distributor. (a) $H = 20$ cm; (b) $H = 30$ cm; (c) $H = 40$ cm.

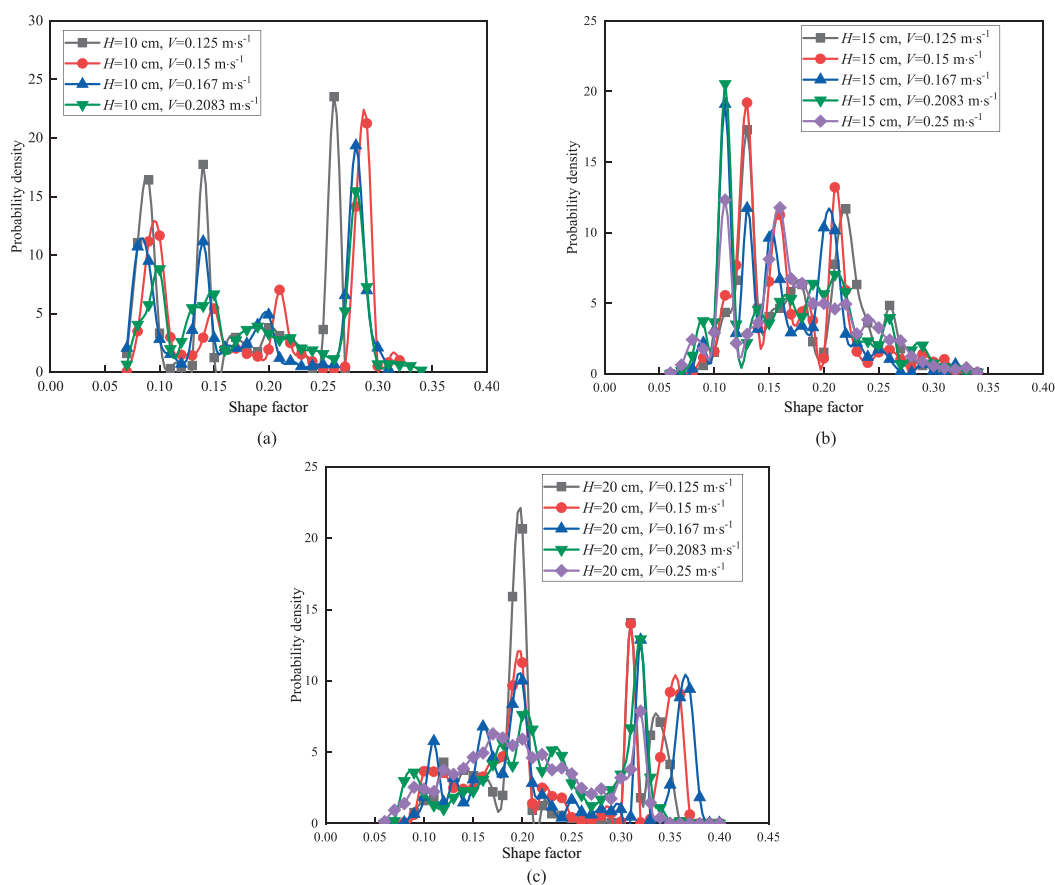


Fig. 14. The SF of @V particles at different bed heights in the TFB with a distributor. (a) $H = 10$ cm; (b) $H = 15$ cm; (c) $H = 20$ cm.

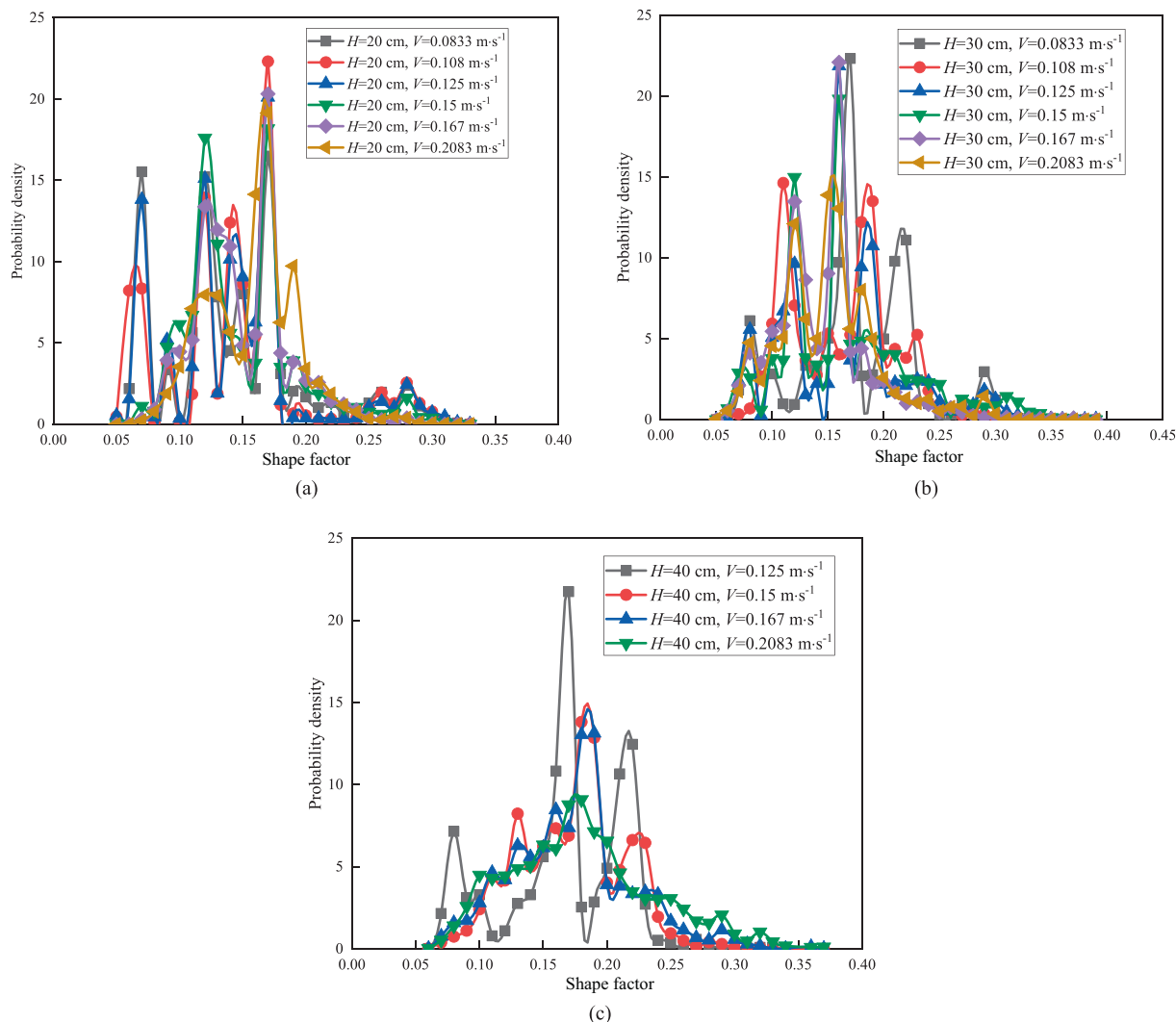


Fig. 15. The SF of $^{\circ}V$ particles at different bed heights in the TFB without a distributor. (a) $H = 20$ cm; (b) $H = 30$ cm; (c) $H = 40$ cm.

(i.e. Region1) and the least bubbles at the bottom region (i.e. Region5) with the increase of gas velocity. On the contrary, when the initial bed is 30 cm in Fig. 21(b), for $^{\circ}V$ particles, there are the most bubbles at the Region5 and the least bubbles at the Region1 with the increase of gas velocity. For $^{\circ}A$ particles, as shown in Fig. 22, we can see that there are the most bubbles at the Region1. The BVF in other regions, however, increases or decreases with the increase of gas velocity. Additionally, the BVF decreases with the increase of initial bed height. The reason that these results are reasonable is that the mass of CNT and bed resistance in the bed of $H = 20$ cm is smaller than that of $H = 30$ cm. The gas velocity can pass through the bed quickly, satisfying the possibility of forming bubbles. The agglomeration structure of $^{\circ}V$ particles makes it easier to store gas, resulting the rising gas velocity of bubbles is less than that of $^{\circ}A$ particles, which is also the reason why $^{\circ}A$ particles have the more bubbles in the Region1 of the bed of $H = 20$ cm and $H = 30$ cm. Nevertheless, combined with the above analysis of bubble motion mechanism, the bubble size formed in the bed of $^{\circ}A$ particles is larger than that of $^{\circ}V$ particles. At the same gas velocity and region, the BVF formed by $^{\circ}V$ particles is greater than that by $^{\circ}A$ particles. As a result, the mixing behavior

of $^{\circ}V$ particles is better than $^{\circ}A$ particles in the tapered angle of TFB without a distributor.

4. Conclusions

In this work, imaging processing is applied to study the motion mechanism and characteristic of bubbles during the CNT fluidization in the TFB with/without a distributor. Fractal dimension is used to analyze the degree of particle movement. Additionally, the mixing behavior of particles in the tapered angle of TFB without a distributor are also reported. Listed below are the major conclusions obtained.

- (1) The motion trajectory and size of bubbles vary greatly with bed materials and bed structure. For $^{\circ}V$ particles, the motion trajectory of bubbles is similar S-shaped, but the observational bubble size is larger in the TFB without a distributor than that in the TFB with a distributor.
- (2) The bubble dynamics is related to bed materials and initial bed height. The largest bubble diameter size appears in the $^{\circ}A$ particles.

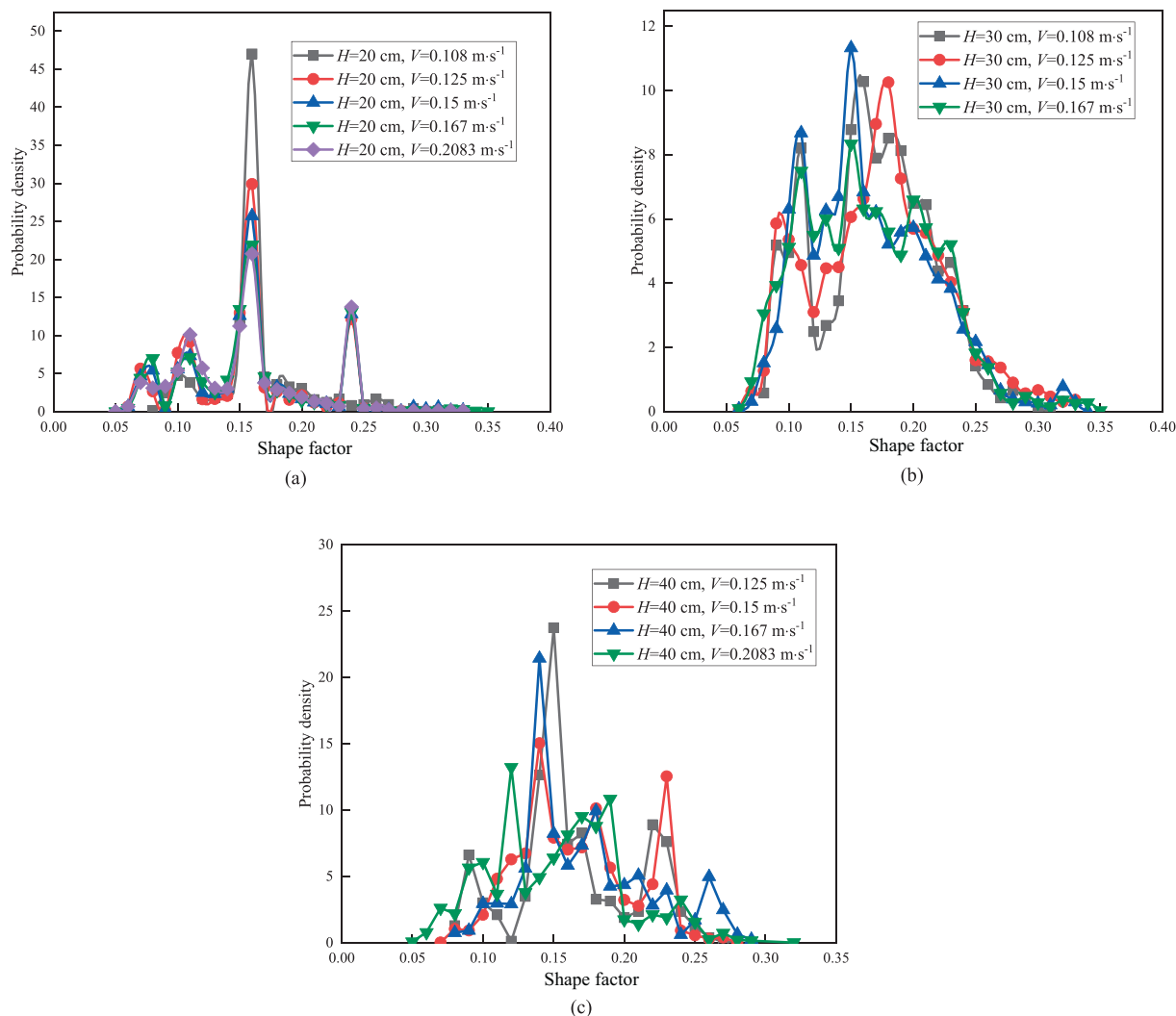


Fig. 16. The SF of A particles at different bed heights in the TFB without a distributor. (a) $H = 20$ cm; (b) $H = 30$ cm; (c) $H = 40$ cm.

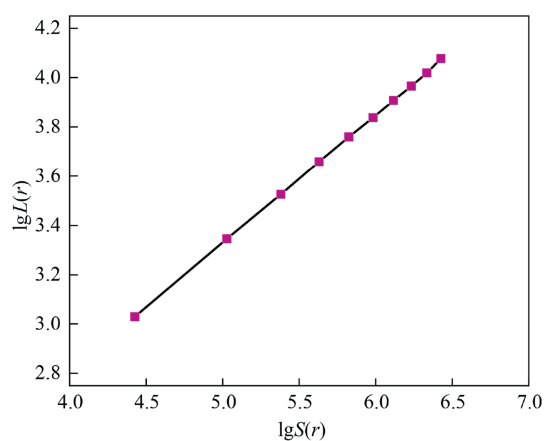


Fig. 17. Fractal dimension of a single bubble. (i.e. $\lg S(r) - \lg L(r)$ curve, $D_f = 2K$, $K = 0.5195$).

- (3) The bubble AR is closely related to bed materials and structure. The bubbles are significantly elongated with the increase of the bed at the same gas velocity due to the role of tapered angle. The probability density distribution of bubble SF in different bed materials is similar.
- (4) The mixing behavior of V particles is better than A particles in the tapered angle of TFB without a distributor.
- (5) Compared to CNT fluidization in the TFB with a distributor, the degree of particle movement will not be decreased or increased alone, and then a platform will be reached to make the average particle movement stable, which will be beneficial to the stable fluidization of the CNT particles.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

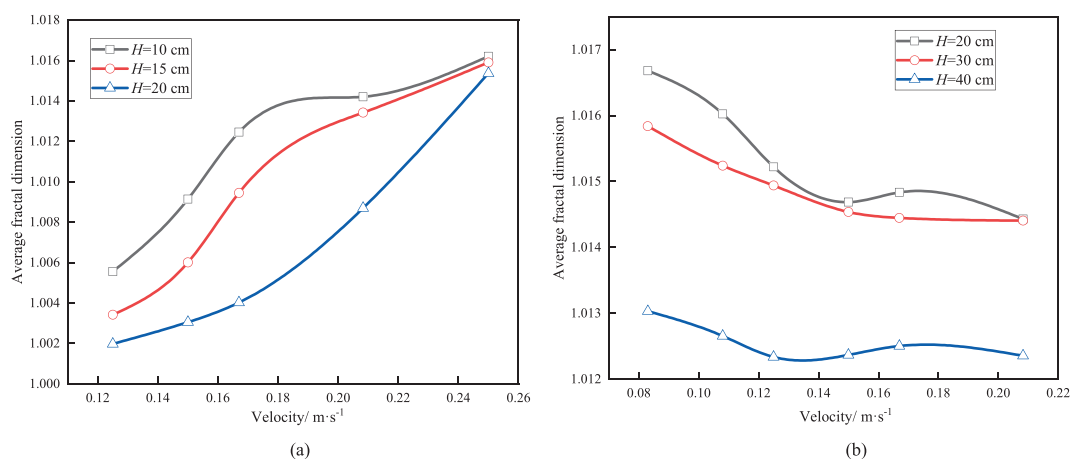


Fig. 18. The average FD of $^{\circ}\text{V}$ particles at different bed heights in the TFB (a) with a distributor, (b) without a distributor.

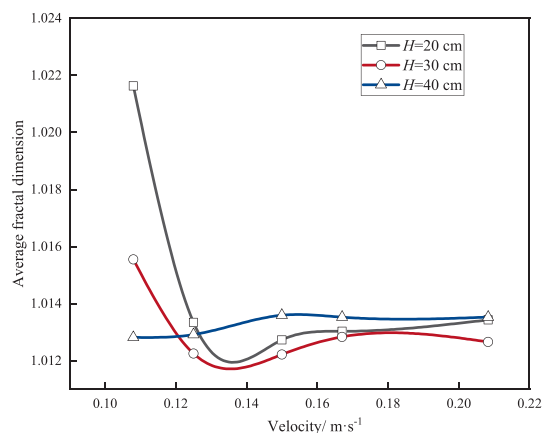


Fig. 19. The average FD of $^{\circ}\text{A}$ particles at different bed heights in the TFB without a distributor.

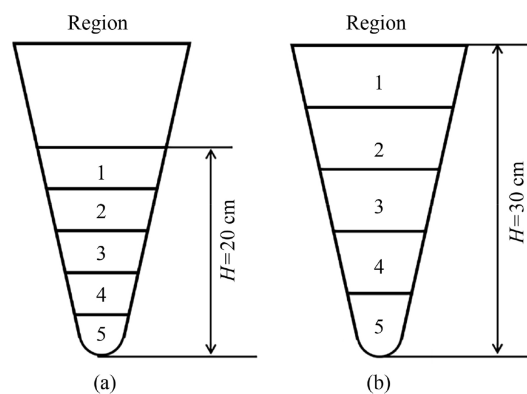


Fig. 20. The schematic diagram of regions division in tapered angle. (a) $H = 20$ cm; (b) $H = 30$ cm.

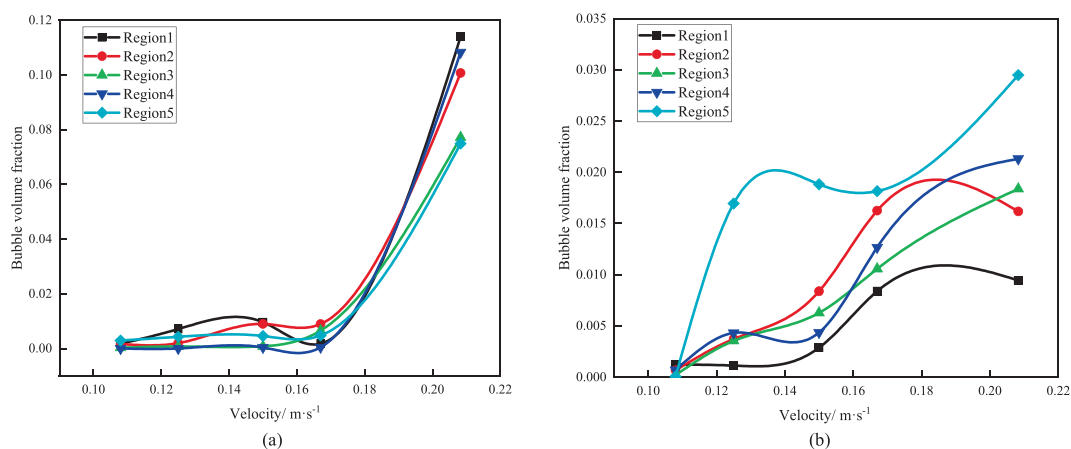


Fig. 21. The BVF of $^{\circ}\text{V}$ particles at different bed heights in the TFB without a distributor. (a) $H = 20$ cm, (b) $H = 30$ cm.

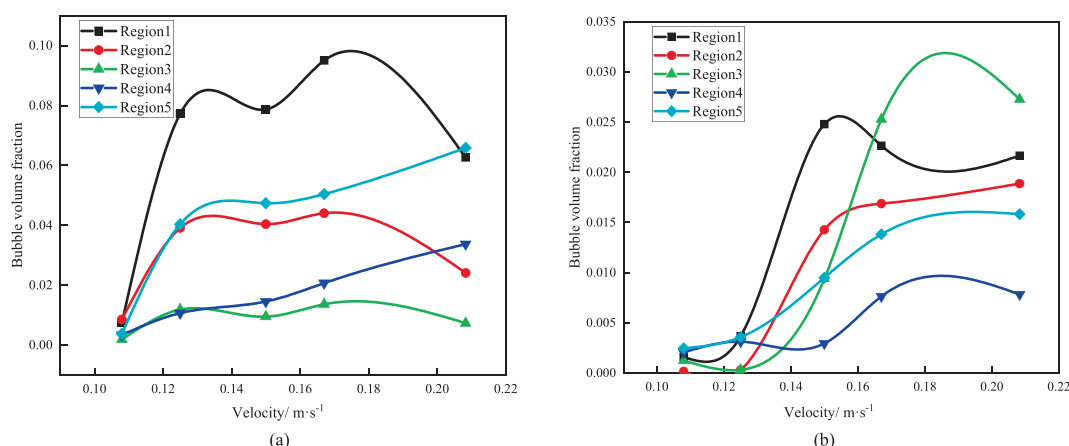


Fig. 22. The BVF of A particles at different bed heights in the TFB without a distributor. (a) $H = 20$ cm, (b) $H = 30$ cm.

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Nomenclature

D_f	fractal dimension
d_b	area-equivalent diameter, mm
d_x	the maximum horizontal dimensions of the bubble
d_y	the maximum vertical dimensions of the bubble
H	initial bed height, cm
$I(x, y)$	grayscale image
$g(x, y)$	binary image
L	bubble perimeter, mm
S	bubble area, mm^2
T	the best threshold value
ρ_b	bulk density, $\text{kg}\cdot\text{m}^{-3}$
ρ_p	particle density, $\text{kg}\cdot\text{m}^{-3}$
ρ_t	true density, $\text{kg}\cdot\text{m}^{-3}$
ε_1	the average void of particle interior

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