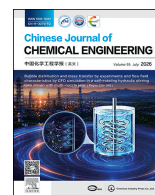




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Full Length Article

Characterization of dynamic behavior in the liquid spray zone of a bottom-spouted fluidized bed

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ABSTRACT

The dynamic behavior and particle shape effects in the liquid spray zone were investigated through temperature standard deviation, liquid–solid contact efficiency, and electrical conductivity signals. Results indicate that temperature standard deviation increases with proximity to the nozzle. Elevated atomisation gas velocity (U_L) reduces droplet diameter and improves their dispersion, which leads to a more uniform temperature distribution and a resulting decrease in standard deviation. The temperature standard deviation is decreased and then increased with the increasing of fluidized gas velocity (U_f). Non-spherical particles had a higher temperature standard deviation than spherical particles. This resulted from particle agglomeration, where lower sphericity led to stronger fluctuations. The liquid–solid contact efficiency is enhanced with the increasing of spouted gas velocity (U_s), U_L , and U_f all. As the liquid spouted rate (Q_L) increased, the liquid–solid contact efficiency, determined by particle capture of droplets, first rose and then declined. Non-spherical particles exhibit higher liquid–solid contact efficiency than that of spherical particles due to longer residence times, and larger contact areas with droplets. Droplet fluctuations are intense near the nozzle, resulting in high electrical conductivity signal intensity. Increased U_s enhances airflow effects, causing frequent voltage signal fluctuations. Flake-like particles accumulate more droplets due to agglomeration, enabling droplets to reach higher bed positions. These studies provide promising research directions for the development of adsorbent pelletization in CO₂ capture.

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1. Introduction

Spouted fluidized bed has the advantages of both spouted bed and fluidized bed [1], with good hydrodynamic characteristics and high efficiency of mass and heat transfer. It has extensive applications and development potential in industrial processes such as particle coating, fine powder agglomeration [2], CO₂ adsorbent pelletization [3], grain drying [4], material mixing [5], coal gasification [6], and pyrolysis [7]. In CO₂ adsorption, the preparation of CO₂ adsorbents is

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the key and core. The preparation process of CO₂ adsorbents involves coating materials, and particle shape is the key factor. The particle shape of some CO₂ adsorbents are similar to the particles used in the article [8]. The spouted fluidized bed generates a regular cyclic motion of particles during the granulation process. This ensures uniform particle mixing and stable mass and heat transfer efficiency. Therefore, the CO₂ adsorbent prepared using a spouted fluidized bed exhibits highly efficient adsorption capacity. However, CO₂ adsorbents are generally non-spherical particles. At the same time, research on the spouted fluidized characteristics of non-spherical particles in spouted fluidized beds remains insufficient. Therefore, investigating the flow characteristics of non-spherical particles within a spouted fluidized bed has become a critical issue.

In actual industrial production, most of the particles are non-spherical particles. Unlike the isotropy of spherical particles in

fluidized motion, non-spherical particles have a lower degree of sphericity, and the obvious anisotropy presented during the flow process [9]. The interaction between particles and turbulence within the bed is more complex, which in turn affects the spouting of spouted fluidized bed. Especially in industries such as particle coating, drug coating and petroleum catalytic cracking, a liquid phase needs to be introduced into the gas–solid flow. In this condition, the liquid entering the fluidized bed forms a liquid spray zone with high liquid content and low temperature [10]. The gas–liquid–solid phases coexist in this region. The dynamic behavior present in the liquid spray zone significantly impacts the quality of fluidized within the bed, which in turn affects utilization rate in industrial production [11]. The research in this area has primarily focused on spherical particles. The impact of particle shape effects on the dynamic behavior of liquid spouting zones remains unclear. To ensure the stable operation of reaction equipment involving non-spherical particles, it is critical to study the dynamic behavior of non-spherical particles in liquid-spray zones. Thus, this has become a key research focus. When the liquid phase is injected into the spouted fluidized bed, some of the droplets contact and collide with the particles. The particles adhere to the agglomeration due to the liquid bridge force between the particles. So, the particle size increases, causing the minimum spouted velocity and the total pressure drop in the bed to increase [12], thereby affecting heat transfer within the bed. The other part of the liquid droplets are evaporated in the bed. So, the apparent gas volume and the gas density in the bed were increased [13]. This increases heat transfer between the gas and solid phases, affecting the temperature distribution within the bed. Nobarзад *et al.* [14] investigated the adsorption capacity and fluidized behavior of silica-coated amine-functionalized multi-walled carbon nanotubes. The CO₂ adsorption capacity of the sorbent mixed with mass concentration of 5% silica nanoparticles was surprisingly increased by approximately 8%, reaching ~3% (mass) of CO₂. Guo *et al.* [15] found that the movement of particles with attached droplets is inhibited due to the increasing of liquid bridge force. So, the annular zone particles' advective energy decreases, which in turn decreases the particle velocity influence on droplet distribution within the bed.

By increasing the humidity within the bed, Zhao *et al.* [16] found that higher humidity accelerates the rate of water diffusion on particle surfaces and also increases the liquid bridge forces between particles, liquid–solid contact efficiency is greater. By research on adding droplets to spouted fluidized beds, the results of Luo *et al.* [17] showed that the wet particles generate significant liquid bridge forces, causes the horizontal motion of particles to weaken, affects the temperature distribution within the bed and the droplet distribution. Particles of different shapes are affected differently by liquid bridge forces, and the degree to which their horizontal motion is reduced also varies. This results in distinct temperature distributions and droplet distributions. The anisotropy of interphase interactions in non-spherical wet granules — covering particle–droplet, particle–particle, and particle–gas contacts — leads to significant differences in liquid–solid contact efficiency [18], which is critical for industrial applications like coating and encapsulation in spouted fluidized beds [19].

This experiment employed three distinct kinds of plastic particles—spherical, cylindrical, and flake-like particles as test materials within a bottom-spouted fluidized bed. Based on temperature signals, this study reveals the influence patterns of temperature dynamics within the liquid spray zone and clarifies the mechanism by which gas–solid flow and interphase heat and mass transfer coupling affect the characteristics of the liquid spray zone. To investigate the influence of droplet dynamic behavior in the liquid spray zone based on the variation of conductivity

signals. The liquid–solid contact efficiency of different shapes of particles in the liquid spray zone was calculated based on the off-line sampling method.

2. Experimental

2.1. Experimental apparatus

The experiment constructed a spouted fluidized bed apparatus with a main body inner diameter of 80 mm, during the experiment, the nozzle diameter D_0 was 8 mm. And the bed frame features a cylindrical structure. The bed frame consists of three sections from top to bottom. These components include the upper cylindrical plexiglass section, the lower cylindrical stainless steel section, a metal air distribution plate with a 60° cone angle, and a fluidized gas chamber. The experimental device consists of five parts: liquid spouted fluidized bed, air supply and dosing system, heating and temperature control system, information acquisition and data processing system, and liquid spouted system. The power of tube furnace is 2000 W. The flow range of peristaltic pump is 0.0053–645 ml·min^{−1}. The spout gas enters the bed through the spout gas inlet after passing through the heating furnace. It is evenly divided into two streams entering the fluidized gas chamber, then enters the bed through small orifices in the gas distribution plate. The schematic diagram of the device is shown in Fig. 1.

2.2. Experimental material

To investigate the influence of particle shape effect on the fluidized behavior, three types of plastic particles were selected for the experiment: spherical polyethylene (PE), cylindrical nylon 6 (Nylon6) particles and flaky particles poly(butyleneadipate-co-terephthalate) (PBAT). They have similar densities and equivalent diameters, but different shape parameters such as shape and sphericity (Fig. 2). The physical parameters of the three particles are shown in Table 1.

2.3. Experimental methodology

2.3.1. Signal detection

Temperature signals were recorded using a Pt-100 thermistor array at axial heights of 20, 70, 100, and 140 mm from the liquid nozzle. The temperature signals from each temperature measurement point were measured simultaneously in the experimental

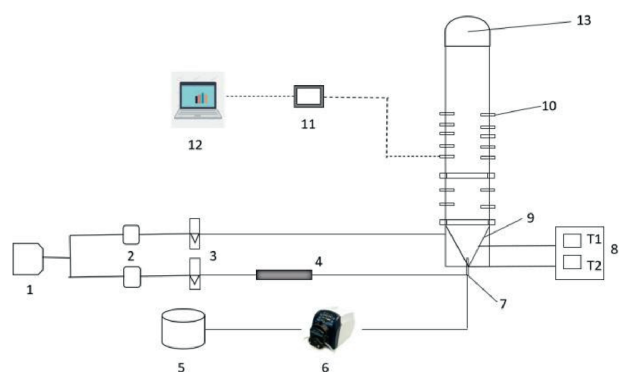


Fig. 1. Schematic diagram of liquid spouted fluidized bed experimental setup: 1—air compressor; 2—buffer tank; 3—rotor flow meter; 4—tube heating furnace; 5—liquid storage tank; 6—peristaltic pump; 7—gas and liquid nozzles; 8—temperature control box; 9—gas distribution plate; 10—measuring holes; 11—data acquisition card; 12—computer; 13—dust collector.

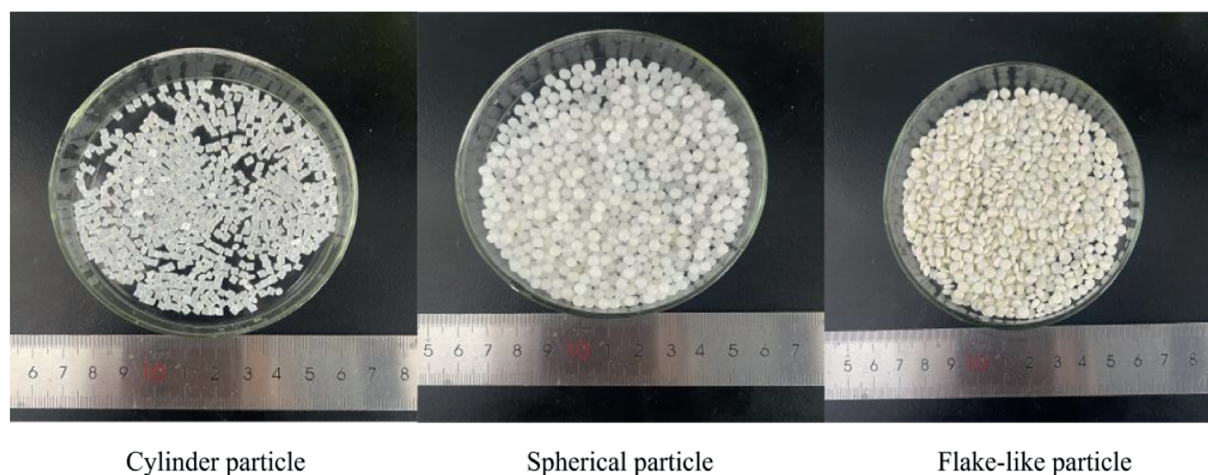


Fig. 2. Photographs of the experimental particles.

Table 1

The physical properties of the particles used in the experiment.

Particle	Shape	Diameter, d_p/mm	Particle density, $\rho_p/\text{kg}\cdot\text{m}^{-3}$	Bulk density, $\rho_b/\text{kg}\cdot\text{m}^{-3}$	Porosity/%	Sphericity	Geldart's classification
Nylon6	Cylinder	2.62	1140	778	32	0.75	Geldart D
PE	Spherical	2.80	1050	850	20	1.00	Geldart D
PBAT	Flake-like	2.80	1260	840	35	0.60	Geldart D

Note: 1. Porosity = $1 - (\rho_b/\rho_p)$, ρ_b is bulk density, ρ_p is particle density.

2. The particles used in the experiment were uniform model particles, the diameter shown is the average diameter.

process, with an acquisition frequency of 1 Hz and an acquisition time of 120 s. The effect of different parameters and shapes on the temperature fluctuation behavior were investigated in liquid spray zones. According to the criteria established under the present experimental setup, the axial position from 20 to 100 mm from the nozzle was designated the bed spray zone, and the position at 140 mm as the spouted drying zone. Before gas is introduced, the bed temperature remains the same for particles of different shapes, not affected by particle shape. This experiment was conducted under steady-state operating conditions, with the measured temperature representing the operating temperature after stabilization.

2.3.2. Detection of droplet signals in the liquid spray zone

A conductivity probe was used to measure the distribution of free liquid droplets in the bed. The conductivity probe consisted of two metal electrodes and a measurement circuit, with the electrodes spaced 0.4 mm apart and each being 5 mm in length. The liquid enters between the two metal electrodes to form a liquid bridge. The circuit is switched on, and a voltage signal can be collected. The more liquid enters the space between the electrodes, the stronger the voltage signal becomes. The conductivity signals at 10, 20, 30, 40, 50 and 60 mm from the liquid nozzle were collected. The experimental process involves simultaneous measurements at each sampling point, with a sampling frequency of 250 Hz and a sampling duration of 120 s. Liquid enters between the two electrodes to form a liquid bridge, completing the circuit. The voltage signal measured by the conductivity probe increases as the volume of liquid between the metal electrodes increases, when the liquid comes into contact with the probe electrode, the voltage rises rapidly. As the liquid continuously evaporates, the volume of liquid inside the electrode decreases, causing the resistance within the circuit to increase and the voltage value to decrease. Under the conditions of this experiment, bubbles cannot form a complete circuit with the two electrodes, making it impossible to detect a signal.

2.3.3. Characterization of liquid–solid contact efficiency

Liquid–solid contact efficiency is defined as the ratio of the amount of liquid entering the bed and contacting the bed material to the total amount of liquid entering the bed. This parameter determines key industrial outcomes, including the degree and uniformity of coating in sectors such as pharmaceuticals and fertilizers. It also significantly influences the liquid–particle reaction rate and the heat transfer efficiency. But this parameter can not be obtained directly, and need to be characterized with the help of some measurements. The liquid used in the section on liquid–solid contact efficiency in the experiment was sucrose solution, sucrose as the solute. The liquid spreads over the particle surface, and the solute coats the particle. The varying amounts of coating applied and the actual capture of particles result in differing masses of solute adhering to the particle surfaces. This calculation demonstrates that the liquid–solid contact efficiency varies for different particle shapes. The liquid–solid contact efficiency was calculated with reference to the characterization method of House *et al.* [20]. The liquid–solid contact efficiency was characterized by mass analysis method.

In the experiments, 60 ml of a 10% sucrose solution was used. The mass of sucrose in the solution is defined as m_0 . The particle mass prior to washing is as m_1 . The mass of washed particles is defined as m_2 . Operating parameters and particle types were varied to investigate their effects on the liquid–solid contact efficiency. The spouted sucrose solution adheres to the particles, and upon liquid evaporation, a sucrose coating forms on the particle surfaces. After the liquid spouted was completed, the air pump was turned off. The bed material was then removed, and the mass of the particles with adhered sucrose was measured using a balance. Following this, the particles were subjected to two washing cycles with distilled water, ensuring that any residual sucrose was fully eliminated. Then the mass of the particles after the removal of the sucrose was measured with a balance. The mass of sucrose adhered to the particles was determined by subtracting the

particle mass after sucrose removal from the initial particle mass. The liquid–solid contact efficiency, now quantified, was used to evaluate the system performance. The calculation formula is: liquid–solid contact efficiency = $(m_1 - m_2)/m_0$.

3. Characterization of Liquid-sprayed Spouted Fluidized Beds

3.1. Temperature dynamic behavior of the liquid spray zone and the spouted drying zone

3.1.1. Particle shape effect

Fig. 3 illustrates the effect of different particle shapes on the temperature and its standard deviation in the spray zone under identical conditions. Within the spouted fluidized bed, the temperatures of the particle phase and gas phase are high, while the liquid phase temperature is low. The droplets were captured by particles, during the particle moving within the bed. Hot air loses heat when it comes into contact with cold liquid droplets, thereby generating temperature fluctuations.

As shown in Fig. 3, flake-like particles yield the highest bed temperature and standard deviation, followed by cylindrical particles, with spherical particles yielded the lowest. The low sphericity of flake-like particles results in a greater contact area with liquid droplets during bed movement. Moreover, non-spherical particles have a greater tendency to agglomerate than their spherical counterparts, thereby the number of free droplets in the region was reduced [21]. During pulsation, droplets released from broken agglomerates re-engage with particles [22], increasing the population of wet particles and droplets within the bed. This leads to more frequent collisions with the thermocouples, causing the measured temperature to fluctuate and the standard deviation was increased. Furthermore, the anisotropy of non-spherical particles induces disordered droplet motion, leading to heterogeneous collisions with the probe and consequently more pronounced temperature fluctuations.

The contact area between particles and droplets critically influences the bed temperature. An increased contact area allows particles to capture and entrain more droplets, thereby reducing the population of free droplets in the spray zone. This reduction, in turn, diminishes the effective gas–liquid contact area and lowers the heat transfer efficiency. Consequently, under identical

conditions, the bed temperature decreases in the order of: flake-like particles > cylindrical particles > spherical particles.

3.1.2. Effect of atomization gas velocity on temperature

Fig. 4 illustrates the effect of different U_L on bed temperature and temperature standard deviation, with all other experimental conditions held constant.

As shown in Fig. 4, as the U_L was increased, both the bed temperature and temperature standard deviation of the three particle types at a distance of 20 mm from the nozzle exhibit a decreasing trend. The primary factor influencing temperature and temperature standard deviation at this location is the droplet temperature. When the U_L increases, the liquid atomization effect improves, leading to more uniform particle distribution within the bed and enhanced heat and mass transfer conditions, thereby the temperature standard deviation was reduced. When the U_L is low, the atomization efficiency of the liquid was adversely affected, resulting in larger droplet diameters. The total contact area of gas–liquid was reduced. Meanwhile, the evaporation rate was slowed. Consequently the temperature within the atomization zone of the bed was raised. As the evaporation of liquids absorbs heat, the increasing of U_L causes droplets entering the bed to be fragmented into smaller droplets by the gas flow. The droplet diameter was reduced. Consequently, the contact area between the liquid and the high-temperature gas stream expands, accelerating the liquid evaporation rate and lowering its temperature. The average temperature exhibits a sustained downward trend.

At the 140 mm measurement position, both the bed temperature and its standard deviation decrease with U_L . This trend is consistent across all three particle types (Fig. 5). According to relevant research [23], under the experimental conditions, the maximum liquid spouted height of the four U_L cannot reach 140 mm. This location is the spouted drying zone. Here, both the temperature and its standard deviation were determined by the gas temperature and particle temperature primarily.

As the U_L was increased, the temperature standard deviation diminishes. This is because the higher gas velocity promotes the formation of a uniform liquid film on the particles. The particles reach the measurement height after the film has substantially evaporated. This evaporation minimized variation in the cooling effect, thereby stabilizing the temperature measurement.

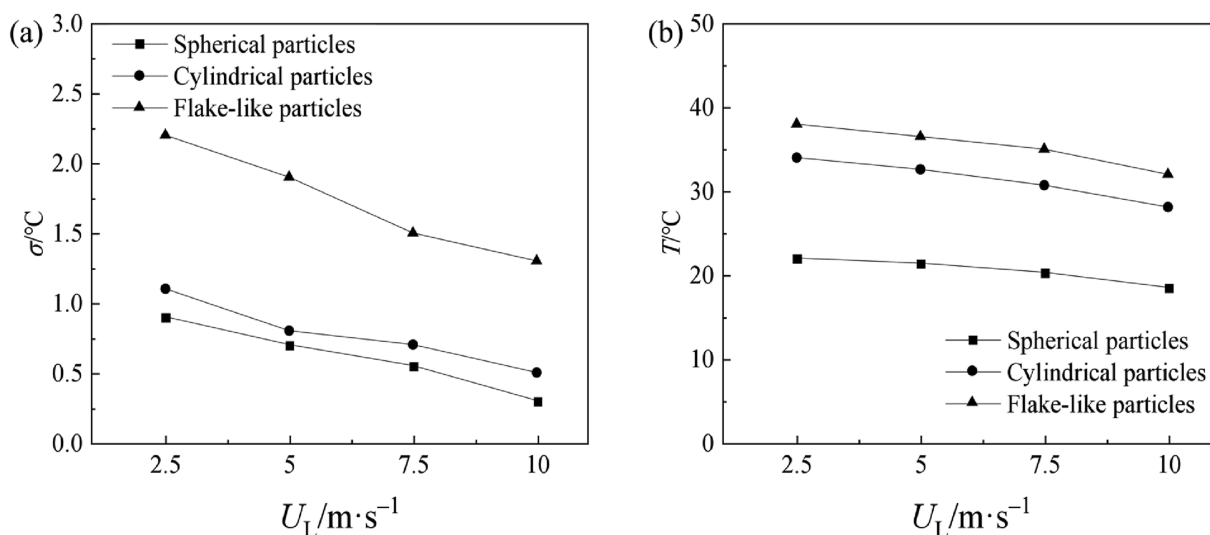


Fig. 3. (a) Standard deviations of bed temperature for three particle size distributions in spouted fluidized flow pattern at an axial height of 70 mm, and (b) temperature variation with atomization gas velocity.

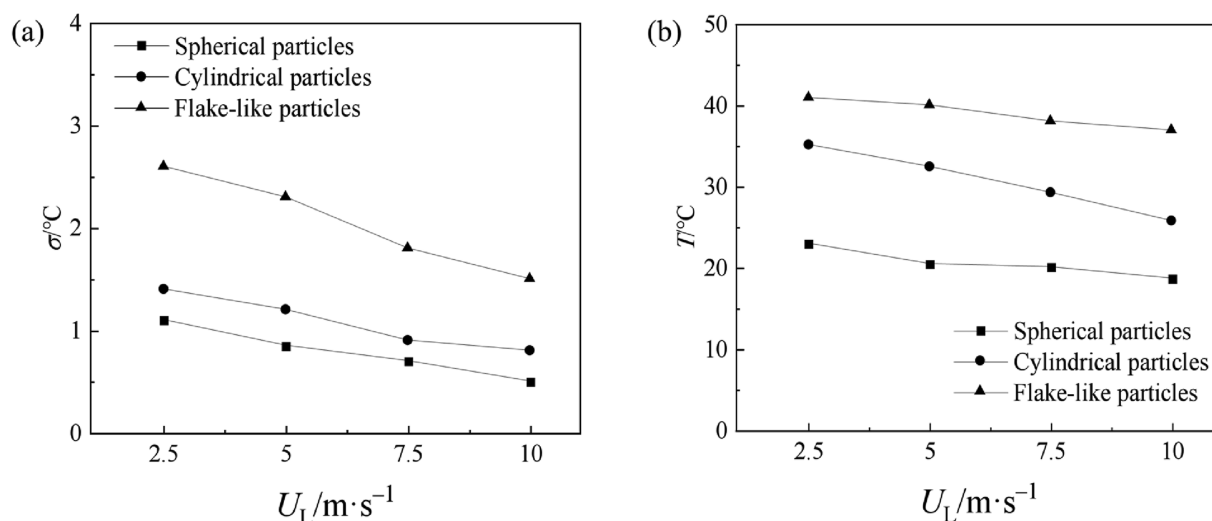


Fig. 4. (a) Standard deviations of bed temperature for three particle size distributions in a spouted fluidized flow pattern at an axial height of 20 mm, and (b) temperature variation with atomization gas velocity.

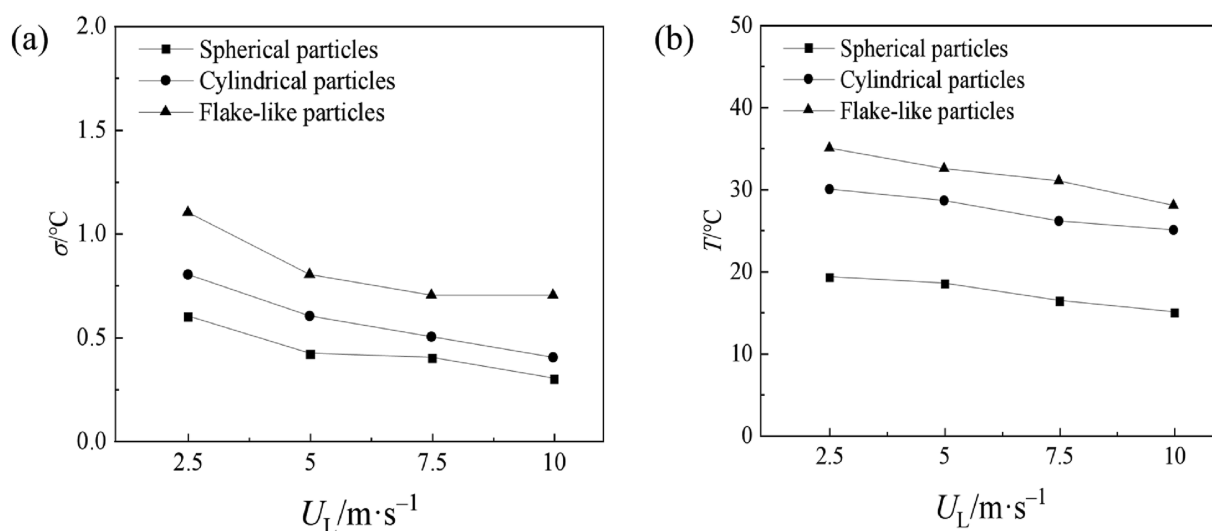


Fig. 5. (a) Standard deviations of bed temperature for three particle size distributions in a spouted fluidized flow pattern at an axial height of 140 mm, and (b) temperature variation with atomization gas velocity.

Simultaneously, the increased U_L enhances the overall liquid evaporation rate, which leads to greater evaporative cooling and a downward trend in the average bed temperature.

On the other hand, as the bed height increases, the cross-sectional area of the conical spouted fluidized bed expands. Consequently, the apparent gas velocity within the bed diminishes with height, leading to a tendency towards thermal equilibrium. The temperature stabilization of particles was achieved through contact with spouted droplets. Furthermore, as the spouted gas stream ascends, its temperature progressively decreases, gradually slowing the evaporation effect on droplets. Compared to the spray zone, the temperature differential within the drying zone progressively diminishes.

3.1.3. Effect of spouted gas velocity on bed temperature

Figs. 6–9 illustrate the temperature standard deviation and gradual temperature increase for three kinds of particles as the U_s increases. Furthermore, temperature fluctuations diminish progressively with increasing height.

The measurement points for this experiment are situated within the pulsation zone of the spouted fluidized bed, with the U_s being the primary influencing factor. The measurement points at 20, 70, and 100 mm lie within the atomization zone. The key influencing factors are gas, droplet, and wet particle temperatures. The principal influencing factors are gas temperature and droplet temperature. The increase in U_s leads to more frequent particle movement, resulting in greater opportunities for particle–particle collisions. Consequently, droplet-to-droplet and droplet-to-gas contact occurs at a higher frequency. The accelerated heat transfer between gas and liquid reduces temperatures near the heating elements. The increasing of elevated gas velocity also increases particle movement speed, diminishing the residence time of wet particles within the spray zone. This reduction in gas–liquid contact time leads to greater temperature variations and increased standard deviation. At a measurement point of 140 mm, the measurement area corresponds to the spouted drying zone. The primary influencing factor is gas temperature. An increase in U_s significantly impacts the total gas volume within the bed. The

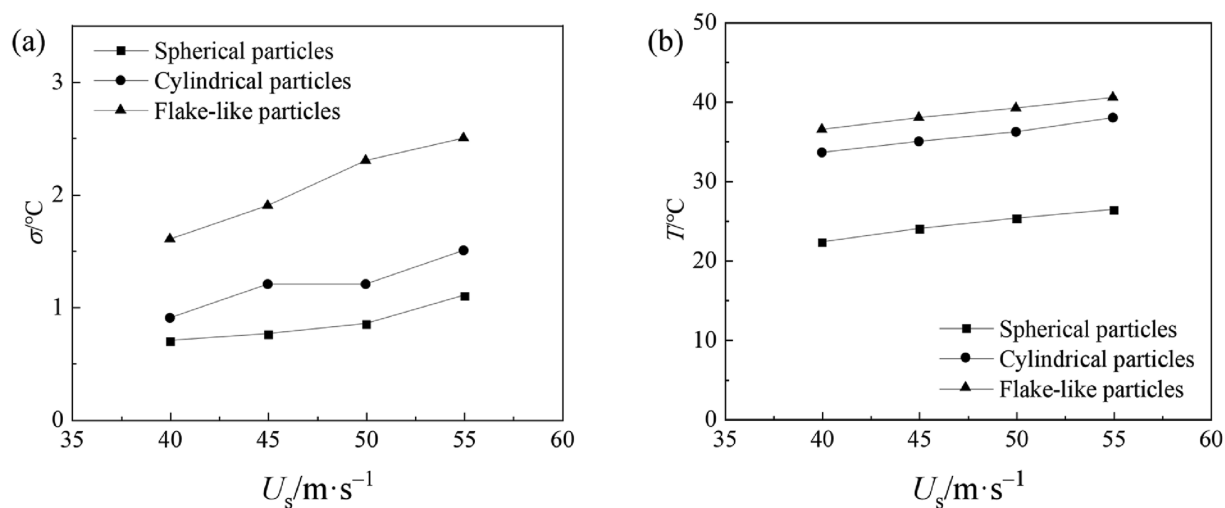


Fig. 6. (a) Standard deviations of bed temperature for three particle size distributions in spouted fluidized at 20 mm, and (b) temperature variation with spouted gas velocity.

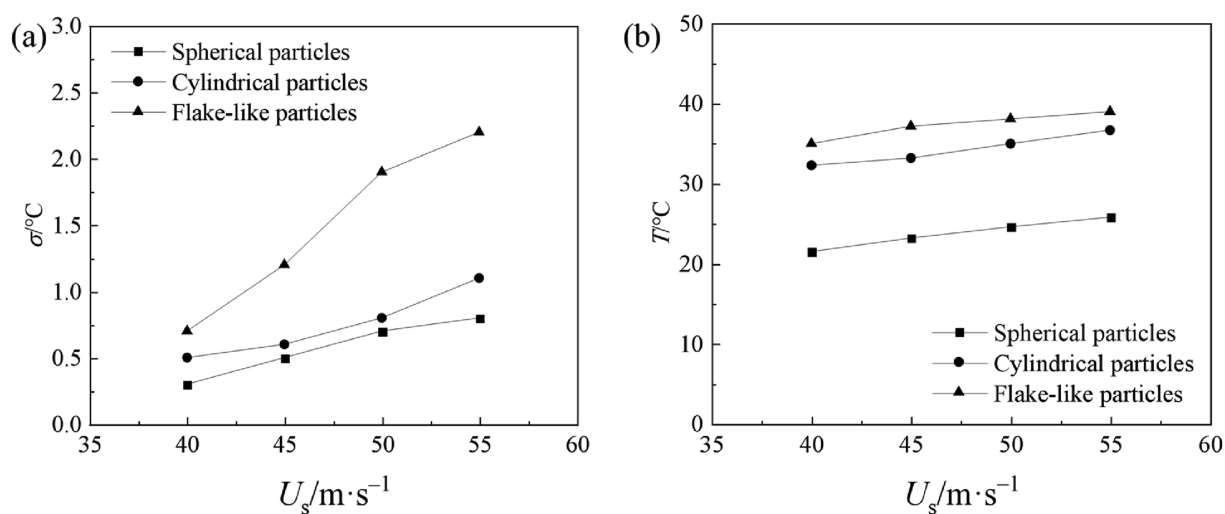


Fig. 7. (a) Standard deviations of bed temperature for three particle size distributions in spouted fluidized at 70 mm, and (b) temperature variation with spouted gas velocity.

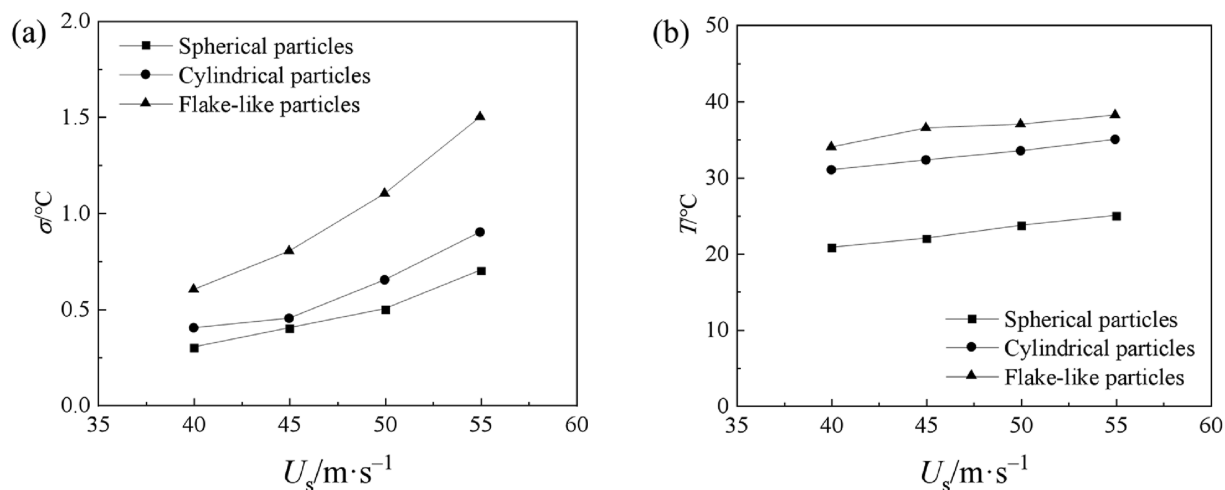


Fig. 8. (a) Standard deviations of bed temperature for three particle size distributions in spouted fluidized at 100 mm, and (b) temperature variation with spouted gas velocity.

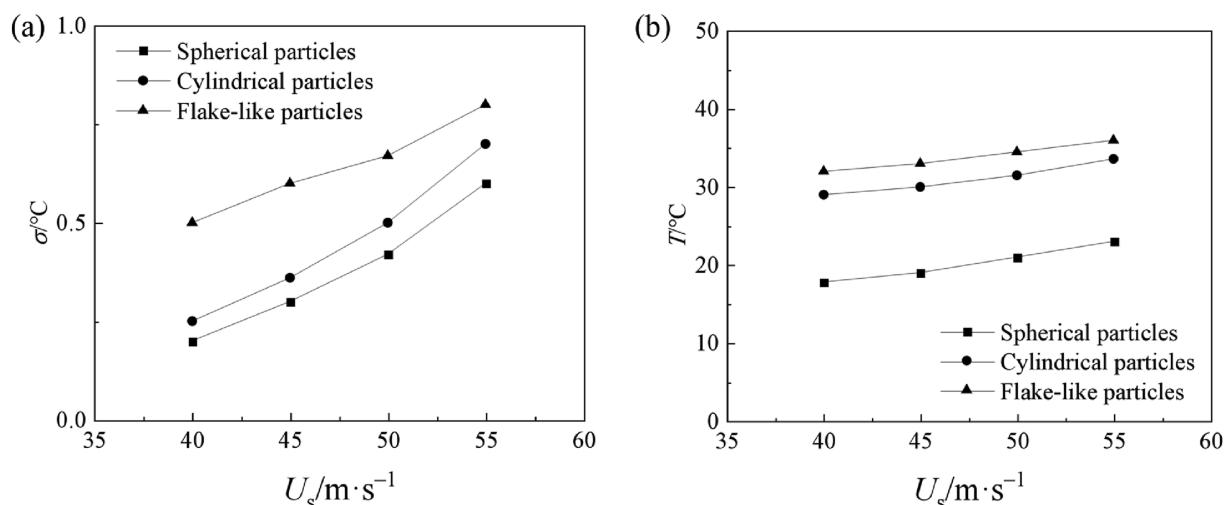


Fig. 9. (a) Standard deviations of bed temperature for three particle size distributions in pulsed fluidized at 140 mm, and (b) temperature variation with spouted gas velocity.

gas is hot air. Increasing its volume introduces more thermal energy into the bed. This causes the bed temperature to rise with the U_s .

3.1.4. Effect of fluidized gas velocity on bed temperature

At the 20 mm position, bed temperature fluctuations first decrease and then increase with higher gas velocity. Meanwhile, the average bed temperature itself shows a steady upward trend (Fig. 10). The primary region affected by the fluidized gas is the annular drying zone. Simultaneously, through the swirl zone at the bottom of the guide tube, a portion of the fluidized gas enters the spray zone, thereby influencing the temperature measurement area. The point of temperature measurement is in the atomization zone. The temperature and its standard deviation are influenced by three factors: gas, droplet, and wet particle temperatures. When the U_f is $0.6 \text{ m}\cdot\text{s}^{-1}$, the temperature standard deviation is minimal. This occurs because at lower fluidized gas velocities, wet particles are insufficiently fluidized. Leading to uneven heat transfer and consequently greater temperature fluctuations with a higher temperature standard deviation. An

increase in U_f causes the wet particles to become fluidized, the movement of particles was stabilized within the bed [24]. This promotes heat exchange equilibrium between the wet particles and the gas. Consequently, the temperature distribution becomes more uniform throughout the bed. This also leads to a gradual reduction in the temperature standard deviation. As the U_f increases further, the gas volume within the bed gradually rises. This expansion of gas volume accelerates the velocity of droplets within the bed. Concurrently, the low temperature of the droplets causes the standard deviation of bed temperature to increase as the U_f continues to rise.

The increase in U_f enhances the total gas volume entering the bed, with the high temperature of fluidized gas. Concurrently, the elevated gas velocity reduces the gas–liquid contact time between the gas and droplets. Thereby causing the increased U_f to elevate the temperature within the bed.

3.1.5. Effect of liquid spouted rate on bed temperature

As shown in Figs. 11 and 12, an increase in Q_L leads to an upward trend in the standard deviation of bed temperature for all three

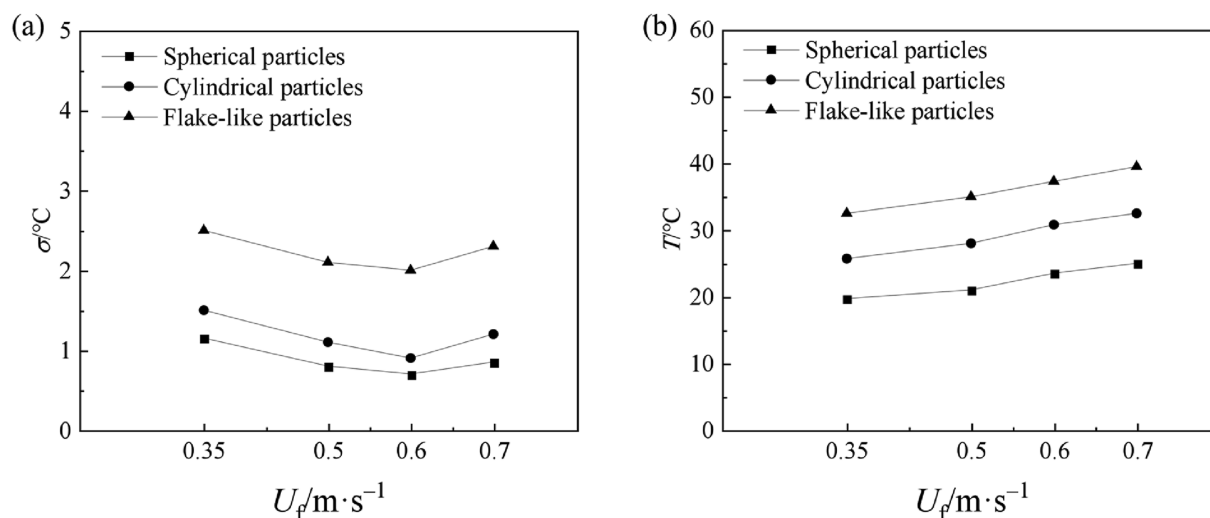


Fig. 10. (a) Standard deviations of bed temperature for three particle size distributions in spouted fluidized at 20 mm, and (b) temperature variation with fluidized gas velocity.

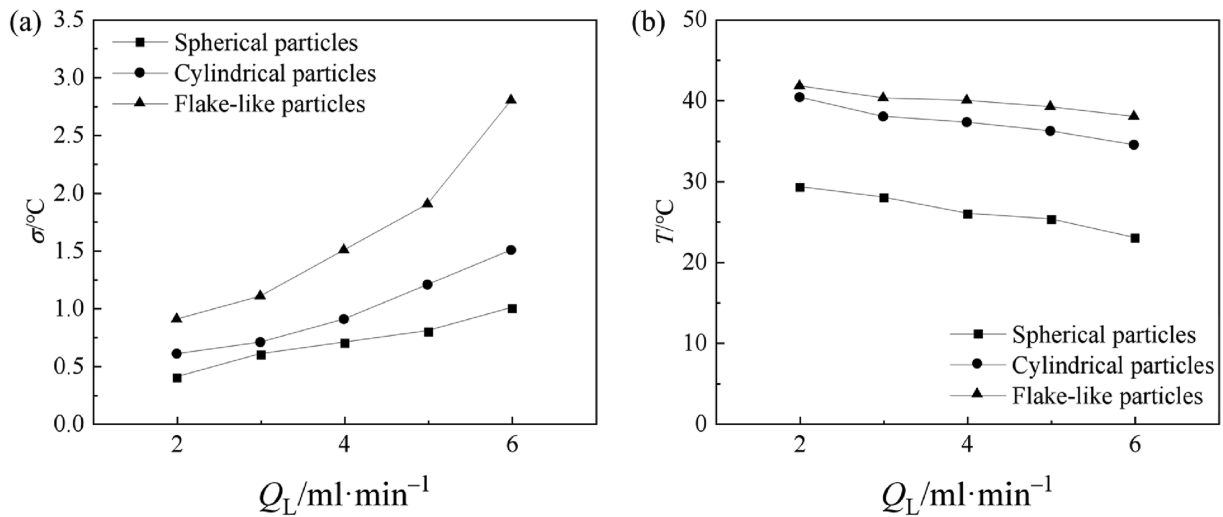


Fig. 11. (a) Standard deviations of bed temperature for three particle size distributions in spouted fluidized patterns at 20 mm, and (b) temperature variation with liquid spouted rate.

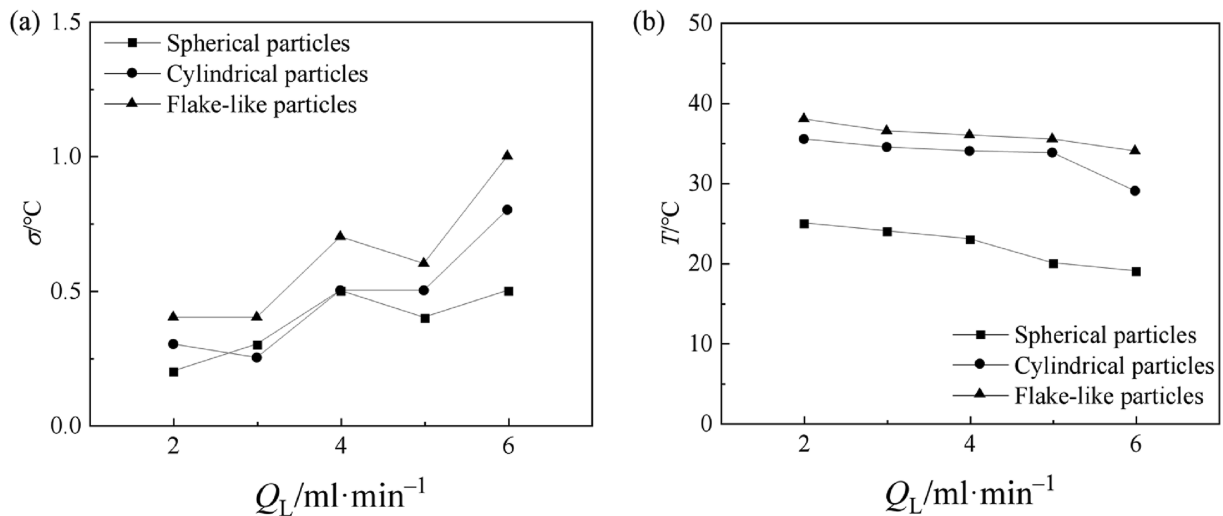


Fig. 12. (a) Standard deviations of bed temperature for three particle size distributions in spouted fluidized patterns at 140 mm, and (b) temperature variation with liquid spouted rate.

kinds of particles. Meanwhile, the bed temperature exhibits a decreasing trend. Furthermore, as height increases, the standard deviation of temperature within the bed diminishes.

An increase in the spouted gas volume raises the liquid holdup in the bed and expands the spouted zone. This increases the probability of droplets contacting the heating elements. Consequently, temperature fluctuations become more pronounced in the spouted zone nearer to the nozzle, resulting in a higher temperature standard deviation. Farther from the nozzle, the higher gas volume also increases the local liquid content. However, the lower ambient temperature in this region reduces the gas–droplet temperature difference, which slows the liquid evaporation rate [25]. As shown in Fig. 12, temperatures fluctuate more markedly away from the nozzle for non-spherical particles than for spherical particles. This is due to the shape effect: droplets colliding with non-spherical particles move with greater disorder within the bed. Consequently, the volatilization of droplets adhered to non-spherical particles by the spouted flow becomes non-uniform [26], leaving a residual liquid influence at greater distances and thus a larger temperature standard deviation.

Fig. 12 shows that the standard deviation of particle temperature were decreased with measurement height. Closer to the nozzle, within the core liquid-spray zone, a higher liquid content causes frequent droplet-probe contact, resulting in a greater temperature standard deviation. Farther from the nozzle, the temperature is lower, which slows the liquid evaporation rate and reduces collision frequency. Additionally, as droplets ascend with the spouted flow, their temperature were decreased. The gas and liquid phases gradually approach thermal equilibrium through heat exchange, thereby diminishing temperature fluctuations at greater distances.

3.1.6. Temperature variation coefficient

Fig. 13 shows the relationship between the temperature variation coefficient and the liquid spouted rate for three particles types. As shown in Fig. 13, the temperature variation coefficient of spherical particles remains below 0.02 under all four conditions. The temperature variation coefficient of flaky-like particles is above 0.04. A decrease in particle sphericity leads to a reduction in the radial distribution of the liquid spout zone within the annular

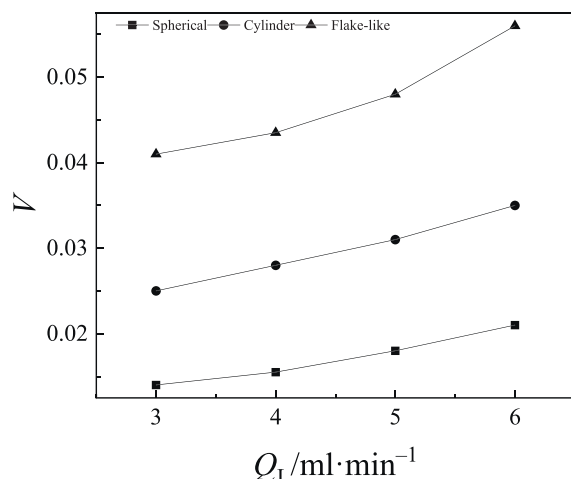


Fig. 13. Effects of different liquid spouted rate on temperature variation coefficient.

area [23]. This thereby reduces the amount of liquid evaporated in the annular region, and causes a large volume of liquid to accumulate at the bottom of the annular region and the annular region–nozzle interface. They are carried into the spout zone by the entrainment effect of the spout gas, this results in an increase in the droplet population within the spout zone. As the number of droplets contacting the probe increases, the temperature variation coefficient measured by the thermal probe rises. Moreover, a higher liquid spouted rate increases the likelihood of droplet–probe collisions. The combined effects of continuous droplet impingement and evaporation lead to an increase in the temperature variation coefficient.

Fig. 14 shows the relationship between the temperature variation coefficient and the height from the nozzle for the three particles types [13]. As shown in Fig. 14, the temperature variation coefficient for all three particle types decreases with increasing nozzle height. At 100 mm, the temperature variation coefficients for the three particle types are all below 0.025. This is because at closer distances to the nozzle, the probe temperature is higher, which in turn leads to a larger temperature variation coefficient. After being ejected, the liquid travels a certain distance, during

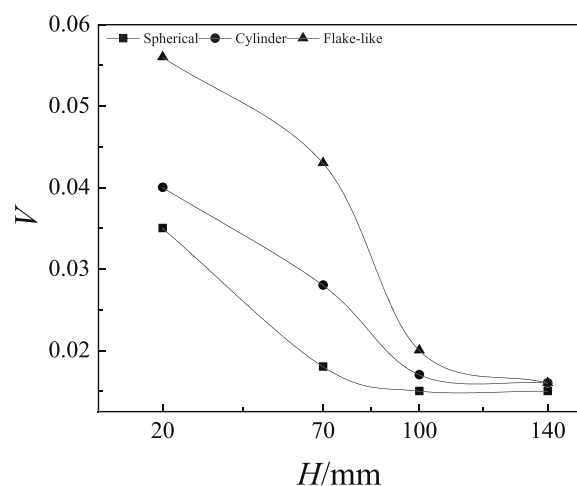


Fig. 14. Effects of different heights from the nozzle on temperature variation coefficient.

which its kinetic energy dissipates. Meanwhile, under the influence of the high-temperature gas flow, both the droplet number and diameter decrease rapidly along the longitudinal direction, the amount of liquid in contact with the probe and undergoing evaporation decreases. Therefore, the higher the measurement point, the lower the temperature variation coefficient. At a height of 140 mm, this area is located within the spout drying zone where droplet content is low; consequently, the temperature variation coefficient further decreases.

3.2. Dynamic behavior of droplets in the liquid spray zone

Fig. 15 shows that the dominant frequency of pressure drop in the spherical particle bed decreases after introducing liquid droplets, while that of non-spherical particles increases, with a more pronounced peak in the dominant frequency. Fig. 15 shows that pressure drops significantly for non-spherical particles after adding droplets. In contrast, it remains nearly unchanged for spherical particles. A lower pressure drop means fewer particles move from the annular to the spray zone. This indicates that the liquid bridge force resists particle movement. This resistance is far greater for non-spherical particles than for spherical particles at the interface. The introduction of droplets increases the bed's apparent gas volume, whilst the reduced mass of particles entering the bed spray zone subjects them to greater gas drag forces. This enhances particle velocity, thereby elevates the fundamental frequency of pressure pulsations. Following liquid spouted, particle adhesion and agglomeration induced by liquid bridge forces reduce rotational kinetic energy [27]. The gas drag force exerted on particles becomes more stable, mitigating the impact of particle anisotropy on pressure pulsations. Furthermore, under the influence of liquid bridge forces, the friction and collision forces between particles and between particles and the tube wall are reduced [28]. Consequently, pressure pulsations in the bed become more regular. The pressure spectrum for non-spherical particles in particular shows a dominant frequency peak with relatively high amplitude.

For the spherical particles, the mass of particles entered the spray zone was larger. The liquid bridging was enhanced with the addition of liquid, which promotes agglomerate formation. The overall particle velocity was slowed due to the greater gravitational force exerted by the agglomerates. Lower agglomerate sphericity increases collision and friction forces [28]. This occurs between the agglomerates and guide tube wall, due to their shape. The increased motion resistance further reduced the overall particle velocity, thereby diminishing the dominant frequency pressure following liquid spouted.

Fig. 16 shows that the voltage signal measured by the conductivity probe over time varies with different U_s of spherical particles, with all other conditions being constant. It can be observed that the closer the distance to the nozzle, the more pronounced the fluctuations in the voltage signal. As the distance from the nozzle increases, the voltage signal measured by the conductivity probe gradually diminishes until it reaches zero. The closer to the nozzle, the less time the atomized liquid has to evaporate. Consequently, the liquid volume within the area increases and is subjected to greater agitation by the spouted stream. This causes liquid to continuously enter and exit the space between the electrodes of the conductivity probe, resulting in pronounced voltage fluctuations. As the distance from the nozzle height increases, the kinetic energy of the spouted gas flow dissipates significantly. Droplets between the probes experience weaker gas flow effects. However, droplets undergo more pronounced evaporation from the hot gas. This evaporation causes the voltage signal to fluctuate. With a further increase in height, the number of free droplets in the bed

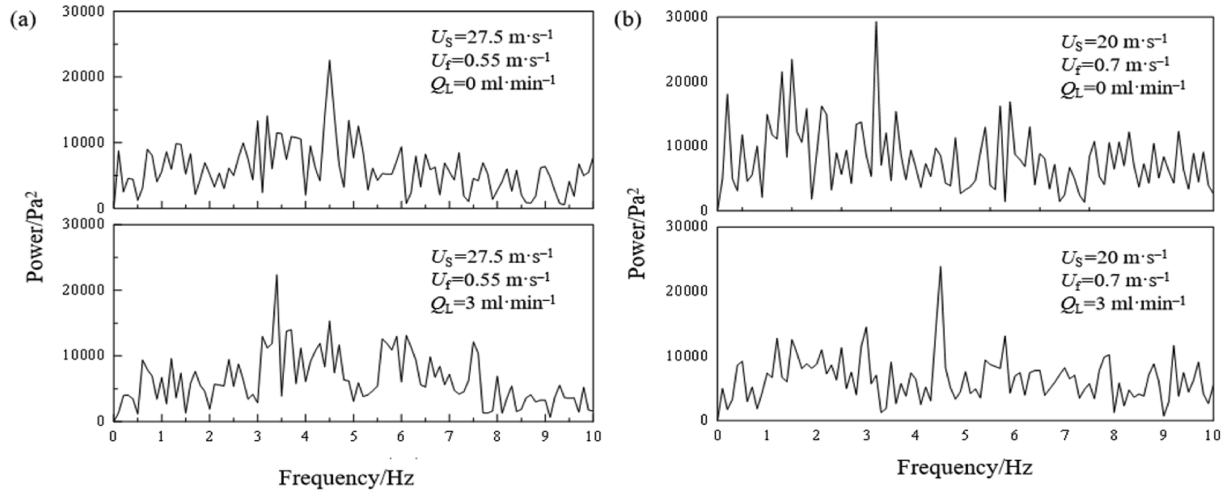


Fig. 15. Variations in droplet pressure drop spectrum introduced by different particle shapes in spouted fluidized: (a) spherical particles; (b) cylindrical particles.

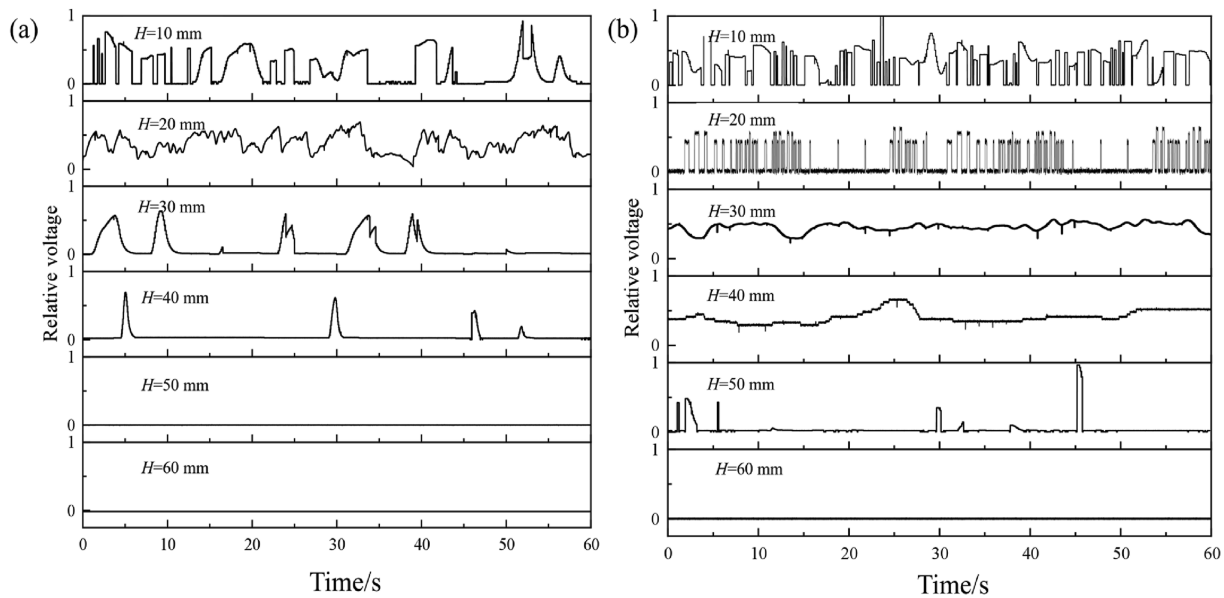


Fig. 16. Electrical conductivity signals over time for spherical particles in a spouted fluidized flow pattern at varying heights from the nozzle ($U_f = 0.7 \text{ m} \cdot \text{s}^{-1}$, $U_L = 5 \text{ m} \cdot \text{s}^{-1}$, $L = 6 \text{ ml} \cdot \text{min}^{-1}$): (a) $U_s = 20 \text{ m} \cdot \text{s}^{-1}$; (b) $U_s = 27.5 \text{ m} \cdot \text{s}^{-1}$.

decreases due to evaporation and adhesion to particles. Consequently, the voltage signal measured by the conductivity probes gradually diminishes until it reaches zero.

Comparing conductance signals at different gas velocities, a key finding was revealed. At higher velocities, probes near the nozzle record more fluctuating voltage signals. Higher U_s produces stronger airflow. This stronger airflow, in turn, accelerates the voltage signal frequency measured by probes near the nozzle.

As shown in Fig. 17, the conductive signals vary over time for particles of different shapes and axial positions. Compared to spherical particles, flake-like particles exhibit detectable voltage signals at a greater height of $H = 60 \text{ mm}$. However, closer to the nozzle, the voltage fluctuation frequency is lower for flake-like particles. This is attributed to their stronger tendency to agglomerate, which reduces the frequency of droplets entering and exiting the probe measurement volume. As the agglomerates rise, some adhered droplets detach. Due to their superior liquid

retention capacity, flake-like particles can carry droplets to relatively higher elevations within the bed.

3.3. Liquid–solid contact efficiency in the liquid spray zone

3.3.1. Effect of bed temperature on liquid–solid contact efficiency

Fig. 18 illustrates the relationship between liquid–solid contact efficiency and bed temperature for three kinds of particles (spherical particles, cylindrical particles, flake-like particles) under U_L of $5 \text{ m} \cdot \text{s}^{-1}$, U_f of $0.7 \text{ m} \cdot \text{s}^{-1}$, and U_s of $40 \text{ m} \cdot \text{s}^{-1}$. The data reveal significant differences in liquid–solid contact efficiency among the three kinds of particles under different bed temperatures. Specifically, the liquid–solid contact efficiency of non-spherical particles (flake-like and cylindrical particles) is greater than that of spherical particles [29].

The variation in liquid–solid contact efficiency among the three kinds of particles stems from differing sphericity affecting the

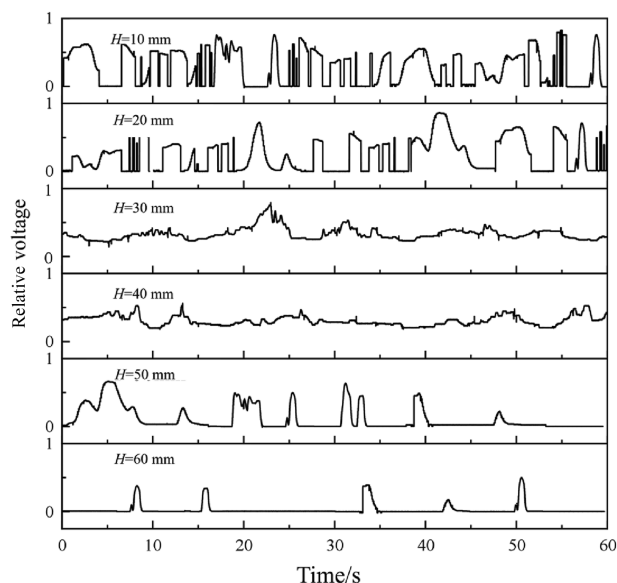


Fig. 17. Electrical conductivity signals over time for flake-like particles at varying heights from the nozzle in a spouted fluidized flow pattern ($U_f = 0.7 \text{ m}\cdot\text{s}^{-1}$, $U_L = 5 \text{ m}\cdot\text{s}^{-1}$, $L = 6 \text{ ml}\cdot\text{min}^{-1}$, $U_s = 27.5 \text{ m}\cdot\text{s}^{-1}$).

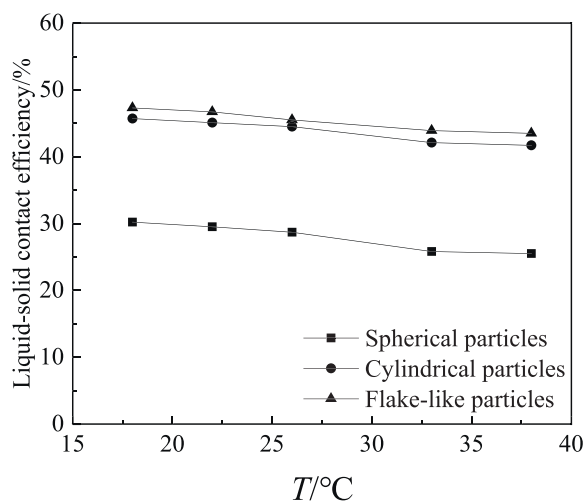


Fig. 18. Liquid–solid contact efficiencies of three particle types in a spouted fluidized bed as a function of bed temperature.

content of free liquid droplets. In the experiment, the sphericity of the flake-like particles was 0.6, that of the cylindrical particles was 0.75, while the spherical particles exhibited a sphericity of 1. The free liquid droplet content in the bed was increased by higher sphericity. Lower sphericity reduces the droplet roll-off tendency, thereby promoting greater contact between droplets and particles [30]. Therefore, the liquid–solid contact efficiency of non-spherical particles is greater than that of spherical particles. Furthermore, the lower the sphericity of the particles, the greater their specific surface area. This increased surface area enhances the collision and adhesion between atomized droplets and particles, which in turn improves liquid–solid contact efficiency. Because non-spherical particles have lower sphericity and thus longer bed residence times [31], they achieve greater liquid–solid contact efficiency through extended contact with droplets.

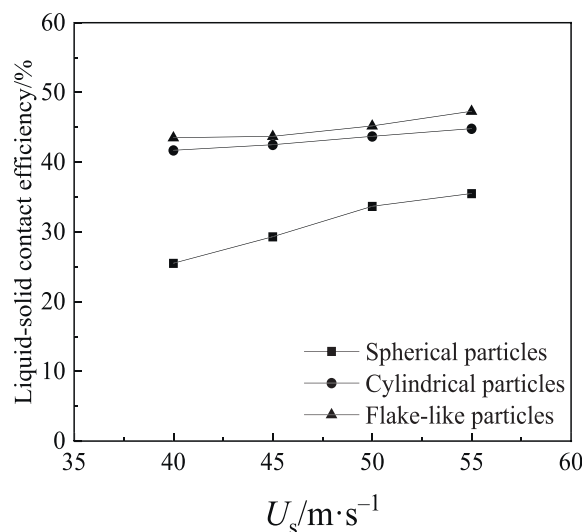


Fig. 19. Liquid–solid contact efficiency of three particle types in a spouted-induced fluidized pattern as a function of spouted gas velocity.

3.3.2. Effect of spouted gas velocity on liquid–solid contact efficiency

Fig. 19 illustrates the relationship between liquid–solid contact efficiency and U_s for three kinds of particles (spherical particles, cylindrical particles, flake-like particles) under U_L of $5 \text{ m}\cdot\text{s}^{-1}$ and U_f of $0.7 \text{ m}\cdot\text{s}^{-1}$.

Experimental studies were conducted at U_s of 40, 45, 50, and $55 \text{ m}\cdot\text{s}^{-1}$. The findings indicate that the liquid–solid contact efficiency increases with rising U_s for the three kinds of particles. As the apparent bed velocity increases, particle velocities also rise, enhancing particle circulation within the bed. This promotes collisions between particles and droplets. It intensifies the capture of atomized liquid by the particles. Consequently, the liquid–solid contact efficiency is elevated. Secondly, liquid–solid contact efficiency depends on the gas–liquid ratio during spouted. A higher ratio improves this efficiency [32]. Higher gas velocity in the bed expands the gas–liquid interface area. This expansion serves to increase the liquid–solid contact efficiency.

3.3.3. Effect of atomization gas velocity on liquid–solid contact efficiency

Fig. 20 illustrates the influence of U_L on liquid–solid contact efficiency for three kinds of particles. Under conditions of $U_s = 40 \text{ m}\cdot\text{s}^{-1}$ and $U_f = 0.7 \text{ m}\cdot\text{s}^{-1}$.

As shown in Fig. 20, the liquid–solid contact efficiency of the three particles increases with rising U_L . Because the enhanced U_L reduces droplet diameter, the dispersion of droplet is facilitated. This improves liquid atomization efficiency and spouted stability while inhibiting particle agglomeration, consequently increasing liquid–solid contact efficiency. On the other hand, the liquid atomization and spouted stability also enhance liquid–solid contact. This improves the efficiency between particles and liquid. Simultaneously, increasing the gas-to-liquid ratio during liquid spouted within the system can also achieve an improvement in liquid–solid contact efficiency.

3.3.4. Effect of fluidized gas velocity on liquid–solid contact efficiency

Fig. 21 illustrates the influence of U_f on liquid–solid contact efficiency for three particles, under conditions of $U_s = 40 \text{ m}\cdot\text{s}^{-1}$ and $U_L = 5 \text{ m}\cdot\text{s}^{-1}$.

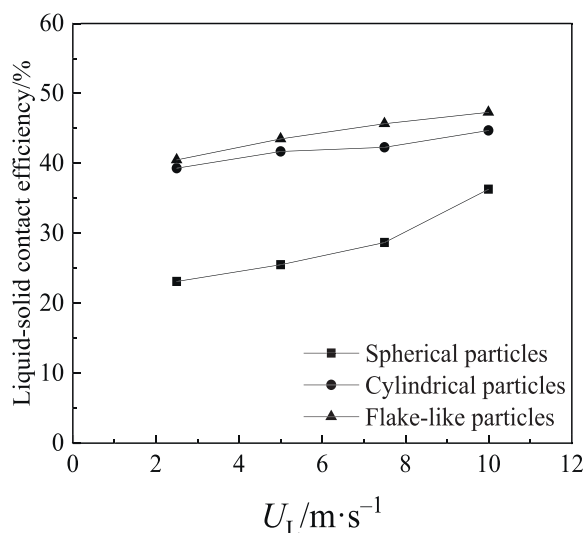


Fig. 20. Liquid–solid contact efficiency of three particle types in a spouted-induced fluidized flow pattern as a function of atomization gas velocity.

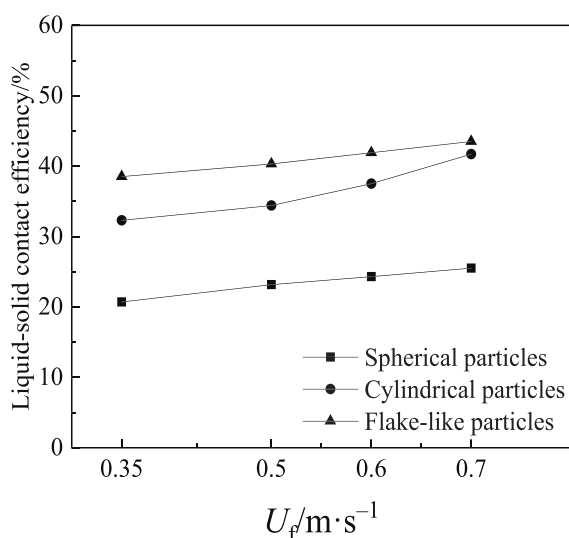


Fig. 21. Liquid–solid contact efficiency of three particle types in a pulsed fluidized regime as a function of fluidized gas velocity.

The liquid–solid contact efficiency of the three particles is enhanced by rising U_f . As the U_f was increased, it directly impacts the annular zone, which in turn increases the inter-particle gaps within the annular zone. This reduction in inter-particle friction enables more particles to traverse the entrainment zone and enter the spray zone. Consequently, the circulation of solid particles within the bed increases, enhancing the particle concentration in the spray zone. This intensifies particle collisions with liquid droplets and improves adhesion. Thereby the liquid–solid contact efficiency is boosted. The greater the gas flow velocity, the faster the evaporation rate of the liquid. Thereby the liquid–solid contact efficiency is enhanced.

3.3.5. Effect of liquid spouted rate on liquid–solid contact efficiency

Fig. 22 illustrates the relationship between liquid–solid contact efficiency and Q_L for three particles.

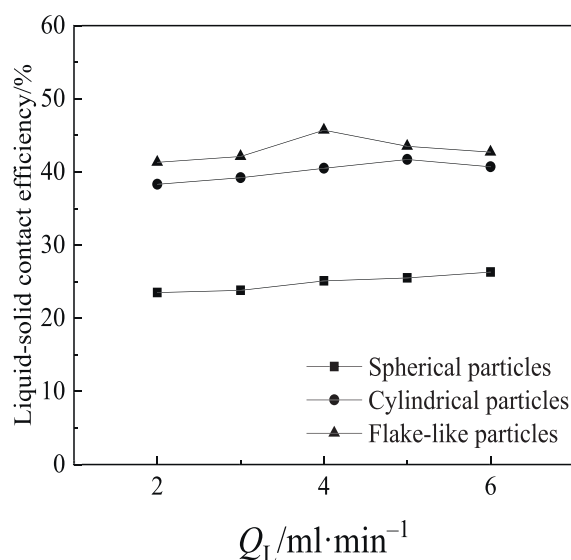


Fig. 22. Liquid–solid contact efficiency of three particle types in a spouted-induced fluidized flow pattern as a function of spouted liquid velocity.

Fig. 22 demonstrates that the liquid–solid contact efficiency for spherical and cylindrical particles exhibits a consistent upward trend from a Q_L of 2 to 5 $\text{ml}\cdot\text{min}^{-1}$. This is attributable to the increased Q_L enabling a greater number of sucrose droplets to enter the bed per unit time, resulting in more droplets adhering to the particles. However, at 6 $\text{ml}\cdot\text{min}^{-1}$, sucrose solution enters the bed rapidly. This causes particle collisions and droplet capture to approach saturation. This results in an excess of sucrose droplets within the bed, preventing adequate contact and adhesion with particles. The efficiency of liquid–solid contact ceases to increase.

Flake-like particles achieve peak liquid–solid contact efficiency at 4 $\text{ml}\cdot\text{min}^{-1}$. Their large interparticle contact area promotes significant agglomeration and wall adhesion. At higher flow rates than 4 $\text{ml}\cdot\text{min}^{-1}$, the viscous sucrose solution causes flake-like particles to agglomerate. These agglomerates then adhere to the vessel walls. This opportunity for droplet-particle contact was reduced, thereby diminishing liquid–solid contact efficiency.

4. Conclusions

This study used a bottom-spouted fluidized bed. Thermocouples and conductance probes investigated the coupled heat and mass transfer among gas, liquid, and solids, as well as the droplet dynamics behavior in the liquid spray zone affected by non-spherical particle shapes. Standard deviation analysis of thermocouple and temperature signals yielded insights into the temperature fluctuation behavior within the liquid spray zone and spouted drying zone. The specific conclusions are as follows.

- (1) Standard deviation analysis of temperature signals revealed the dynamic behavior of temperature distribution within the liquid spray zone and spouted drying zone. Near the nozzle, thermocouples measured a higher temperature standard deviation. This deviation decreased at locations farther away. Concurrently, increases in liquid spouted volume and U_s also lead to heightened temperature standard deviation. As the U_L increases, the temperature standard deviation exhibits a decreasing trend. In contrast, the U_f behaves differently from other parameters: with increasing U_f , the temperature standard deviation is observed to first

decrease and then increase. Non-spherical particles exhibit a larger contact area with droplets compared to spherical particles, making them more prone to agglomeration. This leads to uneven liquid distribution within the liquid spray zone. This results in a higher standard deviation of temperature for non-spherical particles than for spherical ones in the spray zone. Moreover, the lower the sphericity ratio of the particles, the more pronounced the agglomeration becomes, and the greater the standard deviation of temperature fluctuations under identical conditions.

- (2) The relative voltage values processed from voltage signals acquired by the conductivity probe reveal fluctuations in droplets at varying distances from the nozzle over time. Regions closer to the liquid nozzle exhibit greater liquid content and are more strongly influenced by the spouted flow. Liquid continuously enters and exits the electrode gap, generating more frequent droplet fluctuations. As the U_s increases, the time interval between successive voltage signals shortens, indicating accelerated droplet movement and increased kinetic energy. At positions further from the nozzle, the kinetic energy of the spouted gas stream diminishes, with droplets primarily subjected to evaporation by the gas flow. At higher positions, droplets evaporate completely, rendering the probe unable to detect a voltage signal.
- (3) The liquid–solid contact efficiency increases to varying degrees with increases in the U_s , U_L , and U_F . As the Q_L increases, the liquid–solid contact efficiency of the three particles exhibits a trend of initially rising before declining. The peak liquid–solid contact efficiency for flake-like particles is lower than that for both flake-like and spherical particles. Consequently, under identical operating conditions, non-spherical particles achieve significantly higher liquid–solid contact efficiency than that of spherical particles.

CRediT Authorship Contribution Statement

Chengbin Sun: Writing – original draft, Data curation. Meng Wang: Formal analysis, Data curation. Dekang Zhan: Investigation. Tuo Guo: Validation, Supervision. Mingzhou Wu: Writing – review & editing. Man Wu: Writing – review & editing, Funding acquisition. Qingjie Guo: Writing – review & editing, Project administration.

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.

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