INTRODUCTION

Biomass energy is one of the potential renewable energy sources in the world. As the most common biomass materials, plants, wood, and waste are familiar to people and widely used in a broad range of industries.\(^1\)\(^-\)\(^5\) Biomass materials like wood and plants are supposed to be converted into suitable forms of energy through direct combustion, which can be grown energy crops, forest residues, food processing, horticulture, or human waste from sewage plants. Meanwhile, fuel and electricity are the most useful energy forms. Therefore, researchers are attempting to develop more efficient ways to use biomass as fuel and produce more biomass materials for energy production. Over the past decades, biomass energy has been considered to be modernized and popular. However, the high moisture content of fresh biomass materials can decrease the energy efficiency of the conversion process and increase the emission of pollutants.
In general, the initial moisture content of fresh biomass materials is more than 50 wt.% and even reaches up to 65 wt.% sometimes.\textsuperscript{6,7} However, previous research indicated that the moisture content of 10 wt.% is the best operating condition for the combustion of biomass fuels.\textsuperscript{8–10} In order to improve combustion efficiency, therefore, biomass fuels with high moisture should be dried in preliminary treatment processing, which is also known as torrefaction.\textsuperscript{11–14}

Drying pretreatment is of importance to increase the heating value of biomass fuels, thereby contributing to improve cold gas efficiency and the yield of hydrogen and carbon monoxide in gasification.\textsuperscript{15–17} Furthermore, torrefaction technology aims to produce a higher heating value of biomass fuels and a lower calorific value of gas during the process of pretreatment, which thus leads to the generally self-sustained operation of the above process.\textsuperscript{14,18,19} So far, a large number of biomass energy plants are integrated with drying or torrefaction facilities. In general, drying methods are classified according to the operational characteristics of drying facilities. Rotary dryers are the most commonly used devices for the pretreatment of wet biomass particles because of their strong maneuverability and large capacity.\textsuperscript{20–22} It is well known that a rotary drum normally consists of a long cylindrical drum and a number of baffles within it.

To improve heat and mass transfer coefficients, a variety of baffles are supposed to be set up within the rotating drum.\textsuperscript{23–26} Of significance for any rotating drum, baffles are an essential component of inner circumference in the pretreatment system.\textsuperscript{27–29} The shape, size, number, and installation location of baffles can have a direct impact on the drying process by changing the transportation behavior of biomass fuels. They are usually fed into the rotating drum from the higher-level end and then uninterruptedly migrate through picking up and cascading by baffles to the other end. Assessing drying coefficients is the approach to design a rotating drum with baffles. In the industry of biomass pretreatment, wet solid materials are generally lifted from the bottom bed and then cascaded by multiple baffle configurations,\textsuperscript{30} such as straight, L-like, and rectangle L-like types. Due to the difficulties in production and fabrication, baffles are commonly designed to be straight, whose installation slope is set as rectangular. It can be obtained that the mixing behavior of heat and mass transfer takes place in the process of dynamic transportation and exerts a direct influence on drying efficiency.\textsuperscript{31} Nonetheless, little research has been conducted on the effect of baffle structure on the transportation behavior of biomass fuels. Meanwhile, optimizing the structure of baffles can make changes in the residence time distribution (RTD) of biomass fuels.

The cylindrical drum is set on a slight slope to the horizontal axis and rotates around the axis. RTD is always treated as an important index of describing the transportation behavior of particles within the rotating drum.\textsuperscript{32–34} The method of RTD has been widely applied in variety of continuous single or multi phases flow systems.\textsuperscript{35,36} To understand the transportation behavior inside industrial facilities, RTD is commonly estimated and serves as an important property for guidance of efficient operation design and the improvement of system process.

The residence time of transportation is affected by the loading of solid materials along with the rotary drum to a great extent. A variety of investigations emphasized that the performance of a rotating drum with baffles was directly influenced by MRT and RTD. It is fundamental to predict an appropriate feeding mass flow rate as it shapes the demand for products.\textsuperscript{27–29} A longer residence time led to the overdrying of wet biomass fuels and undesirable changes in the size, shape, and properties of materials and even huge energy loss, while a shorter residence time resulted in heterogeneous drying rate and efficiency. As a result, the residence time is a vital parameter for the transportation behavior of biomass fuels. MRT was first calculated as the ratio of the total drum holdup of solid materials to solid feeding mass flow rate.\textsuperscript{40,41} Friedman and Marshall estimated the MRT of spherical solid materials within a rotating drum by using one of the most widely and frequently used empirical equation.\textsuperscript{42} Then, Foust corrected and modified the previous Friedman-Marshall equation\textsuperscript{43} to predict MRT, \( \tau \) as followed

\[
\tau = \frac{13.8L}{\tan I \cdot \omega D^{0.6}} \pm \frac{0.59L}{\sqrt{d_p}} m_g m_s
\]

where \( L, D, I, \) and \( \omega \) are the parameters of rotary drum which are length (m), diameter (m), incline (\(^\circ\)), and rotational speed (rpm), respectively. \( d_p \) represents the diameter of solid materials (m), and \( m_g \) and \( m_s \) refer to gas and solid mass flow rates (kg/h), respectively.

Perry proposed a general correlation to predict the MRT of powders by taking into account the number of baffles without considering the flowing direction of gas-solid two phases. \( f_n \) is the factor depending on the number and structure of baffles.\textsuperscript{44} The correlation was expressed as

\[
\tau = \frac{f_n L}{\tan I \cdot \omega D^{0.6}}
\]

Previous investigations on the behaviors of baffles within a rotary drum from different perspectives indicated that MRT and RTD had a significant influence on drying efficiency by changing holdup, first, and last loading baffles.\textsuperscript{23,45–47} In order to determine and design holdup, a numerical analysis was carried out on the proportion of gasborne and baffle-borne materials along the drum.\textsuperscript{10,48–51} However, publications almost focused on the MRT of particles and ignored RTD. The process of heat and mass transfer occurred all the time when these biomass fuels were...
fed into the rotating drum. Furthermore, drying efficiency was significantly and directly influenced by the transportation behavior of biomass fuels, particularly RTD. As a consequence, the pretreatment approach would give rise to more energy requirements, additional costs, and uncertainties. In addition, the movement manner can directly affect the drying efficiency and characteristics of heat and mass transfer between wet biomass fuels and gas phase. Thus, it is a critical issue on how to determine the transportation behavior and control the residence time of s-liked biomass fuels.

Actually, a variety of nonspherical particles exist in nature and the real world. S-liked biomass fuels are one of the most widely used and common nonspherical particles in industries. S-liked particles are more likely to aggregate because of their extreme thinness. The Go-chess method was developed for the calculation of aggregate surface area by numerical technology. In this paper, it focused on the dynamic transportation behavior of s-liked biomass particles in a rotating drum, which was mainly determined by the structure of baffles. A series of experiments were performed under a variety of operating conditions so as to determine the RTD and flow characteristics of s-liked biomass particles during transportation. A study was carried out on different baffle heights, numbers, installation slopes, rectangular bend heights, and bend slopes, each of which was widely used in the industry. S-liked and CO2 expanded biomass particles were taken as standard experimental materials and tracer particles, respectively.

2 MATERIAL AND EXPERIMENTAL SETUP

2.1 Standard experimental materials and tracer particles

In general, tea and tobacco leaves are representatives of wet biomass particles that are extremely thin and s-liked. Therefore, tobacco leaves usually with large surface areas were employed as experimental materials in this research. In order to prepare fibrous biomass particles, these tobacco leaves were cut into a special size to satisfy experimental requirements. Experimental biomass particles have a width of about 1 mm, an average length range of 23-25 mm, and a thickness of 0.1 mm, as shown in Figure 1. The density and moisture content of biomass materials was 182 kg/m^3 and 15%, respectively, on a wet basis. The selection of appropriate tracer particles was of great importance to perform relevant RTD. Firstly, tracer particles should be easy to detect and small in size during the process of operation. Secondly, they should not have an influence on the flow characteristics of experimental materials. Therefore, CO2 expanded biomass particles were taken as tracer particles in these experiments to determine residence time distribution, as shown in Figure 1. CO2 expanded biomass particles are generally produced in several steps. Firstly, s-liked biomass particles are stored in a cylindrical container where a pressure sensor has already been set. The initial moisture content of s-liked biomass particles is 19%-23%. Secondly, CO2 is continuously filled into the container from the top side until the pressure increases to 27 kg/cm^2. Then, liquid CO2 is transported to the container from the bottom side until it fully soaks s-liked biomass particles. In general, it takes about 15 minutes to finish this process. Left liquid and gas CO2 is recovered for reuse. At this time, a drop occurs in the pressure and temperature inside the container. The state of CO2 within s-liked biomass particles becomes drikold (solid CO2) when pressure is below 0.4 MPa. Then, these particles are selected and transported to an expansion tower. Finally, CO2 expanded biomass particles are obtained after being cooled and humidified.

2.2 Experimental setup and operating conditions

In this paper, heat and mass transfer occurring in the rotary drum was negligible. Therefore, the experimental setup was a laboratory-scale rotary drum at atmospheric pressure and temperature. The rotary drum was made from transparent polymethyl methacrylate in order to observe the behavior of transportation in a clear way. Figure 2 shows that the rotary drum has a dimensional length of \( L = 1850 \) mm and an internal diameter of \( D = 770 \) mm. Baffles with different structures were chosen and fixed on the basis of conditions used in this research.

Experimental biomass materials and gas phase flowed in the same direction along with the rotating drum at the gas velocity of 0.3 m/s and the rotary drum incline of 2°. The mass flow rate of standard biomass particles was 30 g/s, and 30 kg of materials were used under a set of operating conditions. The rotation speed was controlled and set at 9 rpm. The height of baffles without rectangular bend was variable.
and ranged from 64 mm to 154 mm. The effects of baffle installation slopes ($\theta$) 90°, 100°, 110°, and 120° on RTD were observed from tests. The influence of 2, 4, 6, 8, 10, and 12 baffles on dynamic transportation was investigated. The effects of rectangular bend heights ($\Delta$) of 25, 27.5, and 50 mm on RTD were observed from experiments. In order to discuss the effect of bend structure on the flow behavior of s-liked biomass particles, four kinds of bend slopes ($\gamma$) (90°, 110°, 130°, and 150°) were designed and experiments were carried out in the rotating drum. All experimental baffles are shown in Figure 3, and these experimental conditions are summarized in Table 1.

2.3 Experimental setup and approaches

Before tests, the mass flow rate of material, one of the most crucial parameters in this study, should be calibrated. Firstly, the initial mass flow rate was set by the computer in the controller system. Secondly, experimental materials started to be collected into a box when the whole experimental system was steadily run for 10 minutes. The initial time, final time, and the total mass in that box were recorded. Furthermore, the ratio of total mass to time difference was defined as the actual mass flow rate of materials, which was finally calibrated by comparing the actual result and the set value.

Approximately 60 kg of standard s-liked biomass materials were fed into the particle feeder before the operation of the whole transportation system. Then, the door of the feeder was quickly closed in order to decrease the effect of atmospheric moisture on experimental materials. Mass flow rate, rotational speed, and slope of drum, as well as gas velocity, should be set as operating conditions by the computer in the controller system. The mass sensor was set at the first conveyor belt in order to measure the mass flow rate of experimental materials, which can be adjusted by the computer. Information obtained from the computer can help to determine whether biomass materials flowed in a state of equilibrium. Because of their special shape characteristics, these experimental biomass particles were very thin, fibrous, and easy to be mixed and clustered during the process of transportation. However, the phenomenon of clustering would significantly decline drying efficiency in industrial processes. Thus, experimental s-liked materials were transported by the second vibrational conveyor belt that was set before the rotating drum in order to prevent possible of entanglement. Then, these loose materials were fed into the rotating drum. Industrial rotary dryers usually run at an incline range of 2°-4°. Furthermore, the level of input end is higher than that of the output one. Therefore, the experimental drum was set at a slight incline of 2° during the process of transportation.

In order to study the RTD of s-liked biomass particles within the rotating drum, CO$_2$ expanded biomass particles were put into the rotating drum until standard flexible biomass particles were steadily transported achieved a state of equilibrium. Namely, the mass flow rate of standard flexible biomass particles reached the set point. The start time of CO$_2$ expanded biomass particles put into the drum was marked. CO$_2$ expanded biomass particles and standard biomass materials were mixed and transported along with the laboratory-scale rotating drum, of which CO$_2$ expanded biomass particles took up no more than 5% in mass fraction.
Approximately 30 g of biomass mixtures were randomly collected at the exit of the rotating drum in intervals of 10 seconds when tracer particles were visible. Each sample was put into a ziplock bag. Experiments were repeated three times under each set of experimental conditions so as to investigate the transportation characteristics of flexible biomass particles and obtain more accurate results.

Experimental CO2 expanded biomass particles generally went through a three-step process, including washing, separation, and drying. After that, the mass of CO2 expanded biomass particles can be measured. CO2 expanded biomass particles were put into a beaker for 1 minute and washed once with a solution of cyclohexane and ethyl acetate for about 10 seconds. The above steps were repeated three times to separate standard and CO2 expanded biomass particles. After testing, the mass of CO2 expanded biomass particles was measured.

### 2.4 Distribution of residence time

In general, a large number of reactors with different structures were designed in order to increase drying efficiency. It was easy to twist and mix these fibrous particles. Therefore, some baffles or lifters were designed and set in the internal wall to decrease the probability of intertwining. However, detailed information was still insufficient on the flow characteristics of s-like biomass particles during the process of drying. Thus, how to design the structure of baffles and set them attracts a lot of attention. Spectrophotometry method is widely adopted to study the flow behaviors of particles within rotary drums.59,60 Tracer materials were selected to investigate the distribution of residence time.

In order to obtain the transportation behaviors of s-like biomass fuels, it is critical to first answer how to choose a tracker material that must have little difference from experimental materials in size. Moreover, the shape and size of CO2 expanded biomass particles are almost the same with experimental standard biomass particles. Furthermore, density is approximately half that of that of experimental standard particles. Mixtures were collected and put into a special separation solution consisting of cyclohexane and ethyl acetate prepared according to the volume ratio of 2:1. The mixture solution stood steadily for 15 minutes after being fully stirred. Then, the stratification phenomenon of mixtures in the solution would take place due to density difference. It is easy to observe that wet particles at the bottom are the experimental standard biomass particles while those at the top are CO2 expanded biomass particles. Then, standard and tracker particles were weighed, respectively. Finally, the proportion method can be adopted to measure the mass proportion of tracker particles in mixtures (tracker and standard material mixtures).

MRT, mass of holdup, and RTD are three significant indexes used for describing the flow characteristics of particles within a baffled rotary dryer.29 Baffles were normally used to hold up particles, expand their residence time, and increase the contact area between particles and high-temperature gas flow during the drying process. In particular, baffles can stir s-like biomass particles more uniformly to avoid the phenomenon of entanglement. Furthermore, backmixing would increase the residence time of biomass particles. As a consequence, the RTD of particles had a significant impact on the process of heat and mass transfer and drying efficiency. It assumes that the experimental particles are put into the reactor and the ratio of particle mass at the residence time between \( t \) and \( t + dt \) and total mass were expressed as \( E(t) \).

\[
E(t) = \frac{dm}{m} \tag{3}
\]

where \( dm \) is the mass of particles at the residence time between \( t \) and \( t + dt \) and \( m \) refers to the total mass of particles. The relationship between time \( t \) and \( E(t) \) in the rotary drum obeyed normal distribution.

For a sample of biomass materials, the mass ratio of CO2 expanded biomass particles \( (m_{CO2}) \) to total biomass particles \( (m_t) \) was expressed as \( m_{CO2}(t) \). As a function of mass and time, RTD \( E(t) \) was defined by Paredes.61 The RTD of biomass particles by the mass of CO2 expanded tobacco particles over calculated time was determined as follows,

\[
m_{CO2}(t) = \frac{m_{CO2}}{m_t} \tag{4}
\]

\[
E(t) = \int_0^t \frac{m_{CO2}(t)}{m_{CO2}} dt \tag{5}
\]
The negative step method was used to measure and discuss RTD in this research. Mixtures were collected every 10 seconds, and the mass proportion of CO₂ expanded biomass particles was calculated. Therefore, the function of RTD relates to the time and mass proportion of tracker particles. Each experimental condition was repeated three times. Moreover, the mass distribution of CO₂ expanded biomass particles can also be calculated by the Fokker-Planck model below.

\[
\frac{\partial m_{CO_2}}{\partial \phi} = \frac{\partial^2 m_{CO_2}}{\partial \epsilon^2} - \frac{\partial m_{CO_2}}{\partial \epsilon}
\]

\[
Pe = \frac{v_{ax}L}{D_{ax}}
\]

\[
E(\zeta) = \sqrt{\frac{Pe}{4\pi \zeta}} \frac{1}{e^{\frac{D_{ax}}{\zeta}}} \frac{1}{\epsilon}
\]

\[
\zeta = \frac{t}{t_{Taylor}}
\]

\[
t_{Taylor} = \int_0^\infty E(t) \, dt
\]

\[
\epsilon = \frac{x}{L}
\]

where \(Pe\) stands for Pelet number, a fitting parameter for predicting the RTD of solids in an open reactor; \(v_{ax}\) means the velocity of biomass particles in the axial direction (m/s), \(L\) refers to the length of a rotating drum (m). \(D_{ax}\) is introduced as the dispersion coefficient in the axial direction. The coefficient was used to not only determine Pelet number, but also investigate transportation characteristic times by axial dispersion and convection. In addition, \(\zeta\) and \(\epsilon\) are dimensionless properties. \(\zeta\) is the ratio of real-time to MRT \(t_{Taylor}\) developed by Taylor model, which was the most widely utilized model for investigating residence time in various open-open boundary systems. \(\epsilon\) represents the ratio of tracer particles at the axial direction \(x\) and length of the rotating drum.

3 | RESULTS AND DISCUSSION

3.1 | Effect of baffle height on RTD and transport behavior

Experiments were carried out at a baffle height of 64 mm to 184 mm, a rotational speed of 9 rpm, a drum incline of 2°, a gas flow velocity of 0.3 m/s, initial moisture content of biomass of 15%, and a mass flow rate of 30 g/s. Six baffles were installed at the slope of 90° inside the rotating drum. The RTD of s-liked biomass particles was similar to normal distribution. Figure 4 shows the results of experiments under the condition of various baffle heights. Decreasing the height of baffles would narrow RTD because more s-liked biomass particles were mixed and migrated together within the drum. Thus, more s-liked particles were twisted and moved at the same velocity, which demonstrated that more clusters can lead to a reduction in the MRT of particles. Furthermore, it can be observed that increasing the height of baffles would decrease the agglomeration phenomenon of biomass particles. More particles were dispersed by baffles and stayed on them. As a result, the mass of holdup could also increase with the increase of baffle height.

MRTs from the Taylor model of data and experimental measurements for variety of baffle heights are plotted in Figure 5. MRT ranged from 65 seconds to 85 seconds in the above experiments and between 55 seconds and 95 seconds by Taylor model. In general, the direct experimental method agrees well with the Taylor model that demonstrating
that MRT slightly decreased if baffle height increased from 64 mm to 124 mm. In spite of being lifted by baffles, more particles cannot be fully mixed. However, baffles held back s-like particles frequently and enhanced backmixing effect with the increase of baffle height, thereby leading to the increase of MRT from 124 mm to 184 mm. For drying process, increasing the baffle height in an appropriate range would be beneficial to improving drying efficiency.

The results in Figure 4 demonstrated that RTD was slightly affected by the baffle height ranging from 64 to 184 mm. However, the height of baffles had an influence on the mass of holdup and fallout angle. Due to the constant mass flow rate of biomass particles, the mass of holdup was smaller under the condition of 64 mm, and more particles stayed at the bottom of the drum. Furthermore, the baffle was overloaded, as shown in Figure 6A. Scattering angle $\alpha$ was defined as the angle between a baffle and vertical downward direction, as drawn in Figure 6B. In addition, the baffle rotates to a level where these biomass particles started dropping and arrived with the rotating drum at a certain position where all particles fell out from that baffle. At that time, the angle between a baffle and vertical downward direction was defined as fallout angle $\beta$, as present in Figure 6C. Because of overload, the fallout angle of the baffle decreased with the decrease of baffle height. It can be observed that the mass of holdup had a relation with the uploading mass of a baffle. The mass of holdup almost showed no obvious difference under the condition of 94-184 mm because baffles were underloaded. The more time particles spent on baffles, the greater the fallout angle would be. A part of s-like biomass particles near the rotating drum was transported by baffles but would overturn and directly fall back to the bottom if baffle height was not sufficient, which can have an impact on holdup mass and fallout angle. Moreover, particles near the drum would still turn back to baffles and rotated with them under the condition of 154 mm and 184 mm, which thus led to the gradual falling of these s-like biomass particles and an increase in fallout angle. The above analysis demonstrated that the height of baffles had a slight influence on the RTD of s-like biomass particles within the rotating drum, but significant influence on holdup mass and fallout angle. Larger fallout angle and holdup mass would increase the residence time of s-like biomass particles. Further discussions and investigations on baffle height remain to be conducted in order to optimize baffles to satisfy the demand for energy conservation and environment protection.

The effect of baffle height on scattering and fallout angles is plotted in Figure 7 which demonstrates that both angles saw a marginal increase by increasing the height of baffles at a constant mass flow rate. Scattering angle only increased by 16° when baffle height was expanded from 64 mm to 184 mm.

3.2 Effect of baffle number on RTD and transportation behavior

Figure 8 shows the results under the conditions of different baffle numbers ($N_b = 2, 4, 6, 8$), a baffle height of 124 mm, a drum incline of 2°, a gas flow velocity of 0.3 m/s, a mass flow rate of 30 g/s, initial moisture content of 15%, and a rotational speed of 9 rpm. It can be clearly observed that the residence time of s-like particles showed a normal distribution no matter how many baffles were used. The more baffles were set in the inner wall, the longer these biomass particles would stay in the rotating drum. Meanwhile, the residence time of biomass particles at the axis of symmetry was greater with the increase of baffle number, as shown in Figure 8. Consequently, the movement behaviors of particles achieved better consistency and more uniform mixing phenomenon within the rotating drum. Increasing the number of baffles in a certain range contributed to the mixing process of s-like biomass particles and reduced aggregation behavior.

In Figure 9, the results demonstrated that the scattering angle was significantly influenced by the number of baffles and increased with the increase of baffle number. However, fallout angle was slightly affected by the number of baffles. It can be obviously observed that the mass of holdup had a direct impact on the scattering angle of s-like biomass particles in the rotating drum. The decrease of baffle number increased the mass of holdup and reduced scattering angle at a constant mass flow rate of particles. Thus, more particles tended to fall down from baffles under that operating condition. However, it was much easier for particles to stay on baffles because of friction and gravity. Finally, more particles were transported with baffles, which led to a higher...
scattering angle, but a lower fallout angle. Figure 9 shows that the number of baffles had a significant influence on scattering angle, but little effect on fallout angle. All s-liked biomass particles on baffles fell out at the angle of 134°-139° when the number of baffles ranged from 2 to 8. However, scattering angle increased with the increase of baffle number due to the mass of holdup. Particles were more uniformly distributed on each baffle so that fewer particles can stay and rotate with the baffle under the condition of a larger baffle number. Therefore, scattering angle increased from 74° to 99° when baffle number increased from 2 to 8. The above results can provide references for investigating the effect of baffle number on residence time and designing baffles in the field of industrial production. Figure 10 shows the comparison of MRTs obtained from experimental measurement and the Taylor model. Results obtained from both methods indicated that MRT slightly increased with the increase of baffle number. However, MRTs obtained from Taylor model were marginally higher than those obtained from direct measurements based on total mass holdup method. They showed the same changing trends despite some possible errors during several operations.

3.3 | Effect of the installation slope of baffles

The effect of installation slope of baffles ranging from 70° to 110° was experimentally investigated, as shown in Figure 11.
The comparison of MRTs obtained from the experimental data and Taylor model is plotted in Figure 12. The height and number of baffles were 124 mm and 6, respectively. It indicated that the residence time on baffles obviously decreased with the increasing installation slope of baffles. Due to the backmixing of s-shaped biomass particles, the curve of RTD became more dispersive at a larger installation slope. However, the phenomenon of backmixing was weakened with the increase of installation slope. Particles spent less time in staying on baffles, most of which went through the process of lifting and dropping. Fewer particles would be lifted by a baffle if the installation slope was smaller than 90°. Meanwhile, s-shaped biomass particles showed more concentrated RTD, with more particles tending to aggregate. Thus, the MRT of particles was almost the same at the slope of 70° and 80°, and then saw a slight increase from 80° to 110°, as shown in Figure 12. However, the Taylor model failing to take into account the installation position of baffles was just suitable for simple right angle baffles, and can hardly predict MRTs under various conditions like the rectangular bend heights of a baffle. Comparisons are plotted in Figure 13. The resultant force of supporting force and gravity increased with the increase of installation slope, which pushed these s-shaped biomass particles to leave baffles quickly. Therefore, the MRT at the slope of 110° was shorter than that at the slope of 100°.

Figure 13 shows the effect of the installation slope of a baffle on the scattering and fallout angles of s-shaped biomass particles. The results indicated that scattering and fallout angles decreased with the increase of installation slope. As shown in the figure, more particles were expected to drop when the baffle reached to a certain level. Fallout angle was about 150° at the installation slope of 70°, and sharply declined to 127° at the installation slope of 110°, suggesting that particles spent less time in falling and expanded the total residence time during the process of transportation. The effect of drag force between particles and gas flow was strengthened at a larger installation slope. Consequently, enlarging the installation slope in a certain range helped biomass particles to contact with gas flow and avoided the phenomena of aggregation during the process of drying pretreatment. However, heat and mass transfer characteristics can be badly affected when all particles were just transported at the bottom of the rotating drum. It was difficult to effectively utilize higher-level energy at a larger installation slope, which indicated that the installation slope range of 90°-100° was good for the process of drying pretreatment.

**FIGURE 11** The effect of installation slope (θ) of a baffle on residence time distribution of s-shaped biomass particles

**FIGURE 12** The comparison of MRTs estimated from the experimental measurement and Taylor model under different installation slopes of a baffle

**FIGURE 13** The effect of installation slope of a baffle on scattering angle and fallout angle of the s-shaped biomass particles
3.4 | Effect of rectangular bend height of baffles

The results of residence time residence are plotted in Figure 14 which shows that residence time increased with the increase of rectangular bend height. Due to larger rectangular bend height, particles migrated with baffles and turned over to the bend. More particles were lifted by the bend and then reached a higher level, thereby prolonging their residence time in the rotating drum. Most particles spent approximately 56 seconds in staying in the rotating drum at the bending height of 24.8 mm and about 62 seconds for 37.2 mm. In addition, about 15% of s-like biomass particles spent more than 70 seconds in staying in the rotating drum at the bending height of 24.8 mm during the process of transportation. The curves of RTD were near a Gaussian distribution if bend height was larger than 24.8 mm. With its component most dispersedly distributed at the bending height of 62 mm, residence time ranged from 40 seconds to 120 seconds.

Figure 15 demonstrates that the MRT significantly increased with the increase of rectangular bend height. More s-like biomass particles stayed on the baffles in the rotating drum. However, the residence time of biomass particles was more centralized at the condition of rectangular bend height of 37.2 mm. The longest residence time was larger than 110 seconds, while the shortest was about 30 seconds. The difference was larger than that under other conditions. Thus, MRT calculated by Taylor model was obviously different from others. Figure 16 shows that the scattering angle was slightly influenced and decreased from 80° to 72° when bend height increased from 24.8 mm to 62 mm. For s-like biomass particles, the rectangular bend helped to increase holdup mass and fallout angle. However, fallout angle almost remained unchanged with the increasing height of bend due to the constant mass flow rate of particles. It can be clearly observed that some biomass particles dropped from baffles faster at a shorter bend height, while the others were lifted to the same level and fell out under the condition of different bend heights. Figure 16 shows that fallout angle was about 228° for each bend height. Therefore, rectangular bend height can have a significant influence on the RTD of s-like biomass particles, but little effect on scattering and fallout angles.

3.5 | Effect of the bend slope of baffles

Figure 17 depicts the effect of the bend slope of baffles on the RTD of s-like biomass particles. As shown in Figure 18, the Taylor model can predict the changing trend of MRT under the condition of bend slope that ranged from 90° to 130°. Experimental data agreed well with predictions by the Taylor model. MRTs obtained based on Taylor model were slightly less than those obtained by experiment measurements. Figure 19 shows the curves of scattering and fallout angles under the condition of various bend slopes. The maximum proportion of RTD increased at the bend slope of 90° to 130° and then decreased when bend slope reduced to 150°. However, mean residence time was slightly influenced by bend slope as the initial moisture content of s-like biomass particles was about 15 wt.% which was not a very high value. Most biomass particles migrated with baffles more smoothly at lower moisture content, but fewer particles can stay on baffles and be lifted to a lower level at a larger bend slope, as shown in Figure 19.
The maximum residence time was about 110 seconds at the bend slope of 90°, while the minimum was 30 seconds. Figure 17 presents that both minimum and maximum residence time under the above conditions were the same, which meant that bend slope might produce some disturbance to s-like biomass particles and the residence time distributed by a smaller bend slope was more concentrated. Scattering angle was marginally changed from 75° to 79°, while the fallout angle sharply decreased from 227° to 162° at the bend slope of 90° to 150°. The obstruction from baffles reduced with the increase of bend slope because the baffle was more like a rectangle one.

**CONCLUSION**

Based on the current experimental works, the following results demonstrated that RTD was slightly affected at the baffle height of 64-184 mm. However, the height of baffles had an influence on the mass of holdup and the fallout angle. Scattering angle increased from 74° to 99° when the number of baffles increased from 2 to 8. Enlarging installation slope in a certain range helped biomass particles to contact with gas flow and avoided the phenomenon of aggregation. The installation slope range of 90°-100° was good for the process of drying pretreatment. Rectangular bend height can have a
significant influence on the RTD of s-liked biomass particles, but little effect on scattering and fallout angles. Scattering angle was marginally changed from 75° to 79°, while fallout angle sharply decreased from 227° to 162° at the bend slope of 90° to 150°. The Taylor model can appropriately estimate MRT in a rotating drum with variety of baffle structures such as baffle height, number and bend slope. More works should focus on the effects of thermal baffle structures and boundaries within rotating dryers to investigate the transportation behaviors of s-liked biomass fuels in the future.

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NOMENCLATURE

| Symbol | Description               |
|--------|---------------------------|
| D      | Diameter of a rotary drum |
| D_{xx} | Dispersion coefficient in the axial direction |
| dp     | Diameter of solid material |
| f_n    | Factor depends on baffle number |
| I      | Incline of a rotary drum   |
| L      | Length of a rotary drum    |
| l      | Height of a baffle         |
| m      | Mass of materials          |
| m_a    | Gas flow rate              |
| m_{CO2} | Mass of CO₂ expanded biomass particles |
| m_s    | Solid mass flow rate       |
| m_t    | Total mass of biomass particles |
| MRT    | Mean residence time        |
| N      | Number of baffles          |
| Pe     | Peclet number              |
| RTD    | Residence time distribution |
| t      | Residence time             |
| v_{ax} | Velocity of biomass particles in the axial direction |

Greek symbols

| Symbol | Description       |
|--------|-------------------|
| α      | Scattering angle  |
| β      | Fallout angle     |
| γ      | Slope of bend for baffles |
| Δ      | Slope of installation for baffles |
| ε      | Ratio of tracer particles at the axial direction and length of the rotating drum |
| τ      | Mean residence time |
| ζ      | Ratio of real-time to mean residence time simulated by Taylor model |
| θ      | Slope of installation for baffles |
| ω      | Rotational speed  |

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