Self-Sustaining Smoldering Characteristics of Corn Straw Powder Stacks

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ABSTRACT: Biomass fuels are expected to play an important role in future energy consumption. Meanwhile, the fire and explosion of biomass are the have-to-face problems in its production, storage, and application process. This work aims to reveal the influence of stacking and ventilation parameters on the smoldering propagation process and provide guidance for the safe storage of biomass pellets. The effects of stacking density and air flux on the smoldering propagation process were studied experimentally, the variations of bed temperature with these two parameters were analyzed using the numerical simulation technique, and the conditions of self-sustaining smoldering were determined by the local energy analysis method. The results showed that the peak smoldering temperature of corn straw powder was between 500 and 520 °C, and the smoldering propagation velocity was between 10 and 30 mm/h. When the stacking density was changed from 56.89 to 99.56 kg/m³, the peak smoldering temperature change rate was about 2% and the smoldering propagation velocity decrease amplitude was up to 30%. Meanwhile, when the air flux was in the range of 0.2–0.8 m³/h, the small ones had little effect on the peak smoldering temperature, while the large ones helped the peak smoldering temperature reach 560 °C. Finally, the local energy analysis showed that the net heating rate was positive with energy accumulation in the system, the smoldering was self-sustaining, and the smoldering front propagated from the bottom to top. These results provide data support to facilitate the safe storage of biomass pellets.

1. INTRODUCTION

Biomass is considered as a carbon-neutral (short carbon cycle) and sustainable source, which is widely used as a clean renewable energy source.1,2 As the application of biomass fuel becomes more and more extensive, the safety problems in its storage and transportation process become increasingly prominent. Biomass fuels such as straw, rice husk, and sawdust are self-heating solid particles. During biomass storage or transportation, biological and chemical reactions may occur in the stacks.3 These reactions generate heat, and although the heat dissipation is slow in the natural stacking state, the accumulated heat raises the internal temperature of the stacks and eventually causes smoldering.4 Smoldering is a slow, flameless type of combustion that takes place on the surface of porous materials like cellulose and wood fiber insulation, cotton, polyurethane foam, and peat.5,6 Compared to flame fires, it is easier to start and harder to be found and extinguished, and a large amount of harmful gas will be produced during the smoldering process.7 Smoldering can be ignited from a heat source that is not enough to cause combustion, and it is difficult to control once it occurs.8 Once the conditions are appropriate, the smoldering combustion will be transformed into flaming combustion and may even cause an explosion, causing huge property damage and casualties, which is extremely harmful.9,10

Compared with the flaming combustion of the solid, the peak temperature and propagation rate of smoldering are lower.12 Maximum temperatures in smoldering combustion are typically found around 500–700 °C, although both higher and lower levels are reported in some experiments, and the higher temperatures may be attributed to char oxidation.13,14 Moreover, the propagation velocity of smoldering is generally around 10–30 mm/h.

The ignition, propagation, and extinguishment of smoldering depend on its sensitivity to operating conditions and limits.15 Until now, the main evaluation indexes of smoldering are peak smoldering temperature and smoldering propagation velocity. Many scholars have carried out research studies, and the operating conditions studied mainly include air flux, particle size, amount of material, moisture content, material compaction, heating rate, storage geometry, and fuel type.5,16–23 In general, air flux is an important factor affecting
smoldering. Vertical forward smoldering usually occurs when the internal temperature of the stack is too high. However, few experimental studies have been conducted on the vertical forward smoldering propagation of biomass particles with different stacking densities. Therefore, it is of great significance to study the effect of stacking density and air flux on vertical forward smoldering.

Corn straw is a common heating fuel in rural areas, and its volatile content is high, so the ignition temperature is low. At about 200 °C, the volatiles will precipitate in large quantities and begin to burn violently. Therefore, the smoldering caused by spontaneous combustion of stored corn straw powder is worthy of attention. In this work, corn straw powder was selected as the representative to determine the influence of stacking density and air flux on the smoldering propagation characteristics and the conditions of self-sustaining smoldering. The bed temperature variation, peak temperature, and propagation velocity of smoldering were measured experimentally. Also, the local energy analysis of the smoldering front was performed based on thermogravimetry (TG) and differential scanning calorimetry (DSC) data. These results can help us further understand the smoldering characteristics of biomass pellet stacking and provide information for fire safety.

2. MATERIALS AND EXPERIMENTS

2.1. Materials. The corn straw powder was purchased from Lianyungang City, Jiangsu Province of China, as shown in Figure 1. It was milled and sieved with a 5 mm sieve. The initial moisture content of the material was 72.66%.

2.2. Experimental Setup. The schematic diagram of the experimental setup is shown in Figure 2. The smoldering reactor was made of a 5 mm-thick steel plate with a size of 150 mm × 150 mm × 250 mm. To reduce heat loss, a 10 mm-thick insulation was fixed on the outside of the reactor. Three k-type thermocouples with a diameter of 1 mm were set to measure the bed temperature at the central axis and one data point was read every 2 s. The supplier of the k-type thermocouples is Hangzhou Chenyi Instrument Co., Ltd. and the measurement accuracy is ±0.75 t. The electric heating tube used to heat the sample was made of stainless steel, with power of 800 W and power supply voltage of 220 V. Due to the long experiment time, the oil-free air compressor which can run continuously for a long time was used to supply air.

The experimental conditions under different stacking densities and air fluxes are shown in Table 1. The height of the stored material was 150 mm and 56.89 kg/m³ was the natural stacking density of the corn straw powder, which meant that no external forces such as extrusion are applied when filling the material into the reactor. The ignition time was 30 min.

2.3. Thermal Analysis. TG and DSC data were obtained by thermal analysis. Thermal analysis was conducted using a simultaneous thermal analyzer (Perkin Elmer STA 6000). The pyrolysis and combustion analysis experiments were conducted in 99% (V/V) nitrogen and air.

3. HEAT TRANSFER MODEL

3.1. Physical Model and Assumptions. Considering the same heating condition of each cross-section, a two-dimensional model was used to simplify the calculation. The packed bed physical model is shown in Figure 3. The packed bed size was 150 mm × 150 mm.
Table 2. Initial and Boundary Conditions for Numerical Simulation

| initial condition | inlet boundary condition | outlet boundary condition | lateral boundary condition |
|-------------------|--------------------------|---------------------------|---------------------------|
| $T_i = T_0 = 293.15$ K | $T_e = T_0 = 293.15$ K | $T_i = T_0 = 293.15$ K | $\frac{dT_i}{dx} = 0$ |
| $T_e = T_0 = 423.15$ K ($0 \leq t \leq t_0$) | $T_e = T_0 = 293.15$ K ($t > t_0$) | $P_e = P_0 = 1$ atm | $\frac{dT_i}{dx} = 0$ |
| $P_e = P_0 = 1$ atm | $u_e = u_w = 0.0025$ m/s | $A_{s,sp}/V_{sp} = 6(1 - \varphi)/d_p$ (6) |

To simplify the calculation, the following assumptions were accepted:
1. The materials in the porous medium are homogeneous and isotropic;
2. The fluid in the porous medium was incompressible and the fluid flow was laminar flow;
3. The gas satisfies the ideal gas state equation;
4. The porous media particles were roughly spherical.

3.2. Governing Equations. The governing equations to describe the mass and heat transfer processes are as follows:24

3.2.1. Continuity Equation.
\[
\frac{\partial (\rho \varphi u_x)}{\partial t} + \frac{\partial (\rho \varphi u_y)}{\partial y} + \frac{\partial (\rho \varphi u_z)}{\partial z} = 0
\]  
where $\varphi$ is the porosity of the porous medium; $\rho_e$ is the gas density, kg/m$^3$; $t$ is the flow time, s; and $u_e$ is the gas flow velocity, m/s.

3.2.2. Momentum Equation. In the x and y direction, the momentum equations are the following
\[
\begin{align*}
\frac{\partial (\rho \varphi u_x)}{\partial t} + \frac{\partial (\rho \varphi u_x u_x)}{\partial x} + \frac{\partial (\rho \varphi u_y u_x)}{\partial y} + \frac{\partial (\rho \varphi u_z u_x)}{\partial z} & = -\rho \frac{\partial p}{\partial x} - C_1 \varphi \mu s u_x - C_2 \varphi \rho s u_x^2 \\
\frac{\partial (\rho \varphi u_y)}{\partial t} + \frac{\partial (\rho \varphi u_x u_y)}{\partial x} + \frac{\partial (\rho \varphi u_y u_y)}{\partial y} + \frac{\partial (\rho \varphi u_z u_y)}{\partial z} & = -\rho \frac{\partial p}{\partial y} - C_1 \varphi \mu s u_y - C_2 \varphi \rho s u_y^2
\end{align*}
\]  
where $C_1$ and $C_2$ are the resistance coefficients of gas flowing in the porous media and $\mu$ is the dynamic viscosity of gas, kg/(m·s).

3.2.3. Energy Equation. Conservation of energy in the solid and gas phase
\[
\begin{align*}
\frac{\partial}{\partial t} [(1 - \varphi)\rho C_{ps} T_s] & = \frac{\partial}{\partial x} (1 - \varphi)(k_s + k_{rad}) \frac{\partial T_s}{\partial x} \\
& + \frac{\partial}{\partial y} (1 - \varphi)(k_s + k_{rad}) \frac{\partial T_s}{\partial y} + h_{sg} A_{s,sp}/V_{sp} (T_g - T_s)
\end{align*}
\]  
\[
\begin{align*}
\frac{\partial}{\partial t} [\rho \varphi C_{gs} T_g] + \frac{\partial}{\partial x} [\rho \varphi u_x C_{gs} T_g] + \frac{\partial}{\partial y} [\rho \varphi u_y C_{gs} T_g] + \frac{\partial}{\partial z} [\rho \varphi u_z C_{gs} T_g] & = \frac{\partial}{\partial x} (\rho \varphi k_s \frac{\partial T_g}{\partial x}) + \frac{\partial}{\partial y} (\rho \varphi k_s \frac{\partial T_g}{\partial y}) + h_{sg} A_{s,sp}/V_{sp} (T_i - T_g)
\end{align*}
\]  
\[
A_{s,sp}/V_{sp} = 6(1 - \varphi)/d_p
\]  
where $\rho_s$ is the solid density, kg/m$^3$; $C_m$ is the heat capacity of the solid phase, kJ/(kg·K); $T_i$ is the initial temperature, K; $k_s$ is the heat conductivity coefficient of solid particles, W/(m·K); $k_{rad}$ is the radiation heat transfer coefficient, W/(m$^2$·K); $h_{sg}$ is the convective heat transfer coefficient, W/(m$^2$·K). $A_{s,sp}/V_{sp}$ is the specific surface area of solid particles, 1/m$^2$; $C_{gs}$ is the heat capacity of the gas phase, kJ/(kg·K); $T_g$ is the gas temperature, K; and $k_g$ is the heat conductivity coefficient of gas, W/(m·K).

The initial and boundary conditions are shown in Table 2. The boundary condition of the solid phase temperature at the inlet was used to simulate the constant temperature heating at the bottom for a period of time and then the heating was stopped.

4. LOCAL ENERGY ANALYSIS OF THE SMOLENDER FRONT

Smoldering is an exothermic reaction. The released reaction heat is used to maintain the smoldering front propagation. When the local heat loss is greater than or equal to the released and provided heat, the smoldering will be extinguished.25 After stopping the heating, the smoldering front energy was analyzed, and the schema is shown in Figure 4, which mainly includes the reaction heat released by the smoldering, the radial loss part, and the convective air took away part. Because a 10 mm-thick insulation was fixed outside the smoldering reactor, the heat exchange between the reaction zone and the outside was effectively reduced, so the radial heat loss was ignored.

4.1. Reaction Heat Release Rate. The reaction rate was calculated using the Arrhenius formula
\[
k = Ae^{-E/RT}
\]  
where $k$ is the reaction rate constant, s$^{-1}$; $A$ is the frequency factor, s$^{-1}$; $E$ is the activation energy, J/mol; $R$ is the gas constant, J/mol·K; and $T$ is the reaction temperature, K.

The released heat $E_{gen}$ in the reaction zone was calculated using eq 8
\[
E_{gen} = \frac{A_{s,sp}}{V_{sp}}6(1 - \varphi)/d_p
\]
where $\phi$ is the porosity; $k$ is the reaction rate constant, s$^{-1}$; $A_{cs}$ is the cross-sectional area, m$^2$; and $\Delta H$ is the reaction heat, calculated from DSC data, J/g. Since smoldering was a reaction under hypoxic condition, the reaction heat of the sample in air and nitrogen was calculated, respectively, and smoldering was the state between the two.

4.2. Convective Gas Take-Away Heat Rate. The convective gas take-away heat $E_{\text{out}}$ was calculated using eq 9:

$$E_{\text{out}} = - (\rho g A_{w}) C_{p} (T_{w} - T_{0})$$

4.3. Net Heat Rate. The net heat rate of the smoldering front was calculated using eq 10:

$$E_{\text{net}} = E_{\text{gen}} + E_{\text{out}}$$

Equations 8–10 were integrated over time to find the net energy:

$$E_{i} = \int_{0}^{t} (E_{i}) \, dt$$

Therefore, the net heat was calculated using eq 12:

$$E_{\text{net}} = \int_{0}^{t} (E_{\text{net}}) \, dt$$

5. RESULTS AND DISCUSSION

5.1. Smoldering Characteristics under Different Stacking Densities. The smoldering temperature profiles of corn straw powder under different stacking densities are shown in Figure 5. The smoldering propagation process included the ignition, smoldering, and extinguishing stages. After ignition, the temperature of the three thermocouples gradually increased, reached a certain temperature and maintained for a period of time, before entering the rapid heating stage.

After ignition, the temperature of the three thermocouples rose slightly and entered the plateau, respectively. The plateau temperature of $T_1$–$T_3$ was around 90, 85, and 65 $^\circ$C respectively, and the plateau time of $T_1$–$T_3$ increased one by one as shown in Figure 5. With the increase of stacking density, the plateau time of $T_1$–$T_3$ gradually decreased. After the electric heating tube started to work, water evaporation first occurred in the bottom biomass. The water vapor flowed upward through the cooler biomass and condensed when it cooled, then continued to evaporate and absorbed heat as the biomass was heated. Therefore, the temperature changed slowly at higher positions in the reactor. When the heat absorbed by water evaporation roughly equaled the heat released through biomass oxidation, the plateau occurred. Until the water evaporated completely, the biomass began to oxidize rapidly. As the distance from the heater increased, the plateau time increased, as more energy was expended in evaporating the condensed water. This phenomenon was consistent with Yerman’s$^{26}$ and Qi’s$^{23}$ investigations, which showed that the plateau during smoldering of feces and coal was around 100 and 75 $^\circ$C, respectively, also due to water evaporation.

When the biomass filled in the reactor was loose, the stacking density was small, and the top material may have collapsed to the bottom during the vertical forward smoldering process. When the stacking density was 56.89 $\text{kg/m}^3$, the top material collapsed to the bottom. In this case, the temperature of $T_1$–$T_3$ increased rapidly, and the plateau was obvious.

When the biomass density increased, the top material did not fall off, but the increase rate of the temperature was slowed. When the stacking density was 71.11 $\text{kg/m}^3$, the top material did not fall off, and the temperature did not increase rapidly. When the stacking density was 85.33 $\text{kg/m}^3$, the top material did not fall off, and the temperature did not increase rapidly. When the stacking density was 95.56 $\text{kg/m}^3$, the top material did not fall off, and the temperature did not increase rapidly.
kg/m$^3$, two peaks appeared in the smoldering temperature profile as shown in Figure 5a. The second peak appeared because the biomass below smoldered into ash, and the unburned biomass above collapsed down and reacted at the bottom, so the temperature rose again. The collapse of the upper biomass increased the pores in the reactor, enhanced air permeability and oxygen supply, which was conducive to the biomass oxidation. Smoldering may turn into flame combustion, so the temperature of the second peak was higher than that of the first peak. T3 was exposed to air after the collapse of the biomass, and on measuring the gas temperature, the temperature was lower. In Figure 5b, the stacking density was large, and the biomass collapsed slowly during smoldering, so only one peak appeared in the temperature profile. However, the temperature of T3 was significantly lower than that of T1 and T2. The reason was that T3 was exposed to air and on measuring the gas temperature due to the collapse of the upper biomass, the temperature was relatively low. In Figure 5c, the temperature of T3 was approximately the same as that of T1 and T2. At this time, the stacking was stable without collapse, the oxygen supply was sufficient, and the smoldering front spread slowly. Finally, in Figure 5d, the temperature of T3 was relatively low. Compared with other scenarios, the stacking density of 99.56 kg/m$^3$ left a few pores with insufficient air supply. Thus, most of the oxygen was consumed at the bottom, while there was insufficient oxygen supply at the top, which limited the reaction, resulting in the lower peak temperature.

The total smoldering time was defined as the time required from the end of ignition to the temperature of each thermocouple falling below 50 °C. The experimental results are shown in Table 3. With the increase of the sample mass in the reactor, the stacking density and the total smoldering time increased. The larger the sample mass was, the longer the total smoldering time would be. Meanwhile, increasing the stacking density reduced the pore size, restricted the oxygen supply, and reduced the smoldering rate, so the time to complete the reaction increased.

Except for experiment 1, T1 and T2 had little difference in the peak temperature and conformed to the characteristic peak temperature of smoldering. With the increase of stacking density, the peak temperatures of T1 and T2 generally showed a downward trend. The upper sample in the reactor collapsed in the process of vertical forward smoldering. Therefore, T3 measured gas temperature in most cases and its peak temperature was significantly lower than that of T1 and T2, which did not conform to the characteristic peak temperature of smoldering. This indicated that the smoldering reaction mainly occurred at the bottom of the reactor, so the influence of stacking density on T3 peak temperature was not discussed. The peak temperature recorded by the thermocouple in each experiment was 602, 518, 518, and 506 °C, respectively. Except for the serious collapse in the first experiment, in which smoldering might turn into flaming combustion, the stacking density had little influence on the peak smoldering temperature.

In this paper, Fang He’s research$^{19}$ was referenced to calculate the smoldering propagation velocity. The propagation velocity of the drying front was the distance between two adjacent thermocouples divided by the time interval between the two thermocouples reaching 101 °C. The propagation velocity of the carbon oxidation front was the distance between two adjacent thermocouples divided by the time interval between the two thermocouples reaching the peak temperature. The calculation results are shown in Table 4. Due to the serious collapse in experiment 1, two peaks appeared in the temperature profile, so no calculation was done.

![Table 4. Smoldering Propagation Velocity under Different Stacking Densities](https://doi.org/10.1021/acsomega.1c00786)

The propagation velocity of the drying front in T1–T2 was higher than that in T2–T3, because T2–T3 was far from the bottom heater and the temperature was lower, the drying time increased and the propagation velocity of the drying front decreased. With the increase of the stacking density, the propagation velocity of the drying front in T1–T2 decreased, because the water was easier to evaporate when the stacking was loose. At the natural stacking density of 56.89 kg/m$^3$, corn straw powder was loosely stacked and the pore size was large, so the water evaporated quickly. The propagation velocity of the drying front in T2–T3 changed little with the stacking density. This stacking density had little influence on the propagation velocity of the drying front at lower temperatures.

The experiment was not in accordance with the characteristics of propagation velocity. Because the reactor was filled with fewer samples, the stacking density was smaller, the porosity was larger, the reaction proceeded faster, and the collapse phenomenon existed. Therefore, the time for T1–T3 to reach the peak temperature was relatively close, and the calculated smoldering propagation velocity was high. When the stacking density was high, the pore size of the reaction zone was small and the reaction proceeded slowly. The collapse phenomenon in the reactor, especially at the bottom of the reactor, was relatively light and the smoldering front spread slowly along the bed. At this time, the calculated smoldering propagation velocity was more accurate. In experiments 2 and 3, the smoldering front propagated slowly from the bottom to top, and the propagation velocity in T1–T2 was lower than that in T2–T3. The reason was that the T1–T2 section started to react from low temperature and the...
T2–T3 section was preheated for a period of time when the reaction occurred. Since increasing the temperature of reactants can increase the reaction velocity, the smoldering propagation velocity of T2–T3 was relatively large.

Increasing the stacking density, the smoldering propagation velocity in T1–T2 decreased. Because more samples were accumulated per unit volume, the pore space was reduced and oxygen supply was insufficient, which reduced the...
smoldering propagation velocity. The smoldering propagation velocity in T2–T3 changed little with the stacking density.

In conclusion, the stacking density had little influence on the peak smoldering temperature. With the increase of the stacking density, the propagation velocity of the drying front and the smoldering propagation velocity in T1–T2 decreased. While the propagation velocity of the drying front and the smoldering propagation velocity in T2–T3 changed little with the stacking density.

5.2. Variation of Bed Temperature with Stacking Density. In COMSOL, a two-dimensional model was established, and the number of grids divided was 5625 (75 × 75). The bottom was heated at a constant temperature of 150 °C for 20 min, and T1, T2, and T3 are 60, 90, and 120 mm from the bottom, respectively.

Figure 6 shows the temperature profiles of T1–T3 when the air flux was 0.2 m³/h and the stacking density was 56.89, 71.11, 85.33, and 99.56 kg/m³, respectively. The higher the stacking density was, the slower the heat transfer was, and the lower the bed temperature reached within the same time, the maximum difference can be about 10 °C. The reason was that the increase of solid particles per unit volume increased the airflow resistance and decreased the flow velocity. The convective heat transfer between solid particles and air was weakened, and the heat transfer by heat conduction was relatively slow. Therefore, when the stacking density was high, although oxygen supply was limited, heat loss was also hindered, leading to an increased risk of smoldering.

5.3. Smoldering Characteristics under Different Air Fluxes. The air flux in three experiments was 0.2, 0.4, and 0.8 m³/h, respectively, and the results are shown in Figure 7. The plateau temperature of each measurement point was roughly the same in the three experiments, which was about 90, 85, and 65 °C, respectively, and the plateau time of T1–T3 increased one by one. With the increase of air flux, the plateau time of T1 gradually increased because the increased gas velocity took away more heat, and the drying process took a longer time. While for T2 and T3, which were located above, the plateau time was less affected by the air flux.

When the air flux was 0.2 and 0.4 m³/h, the smoldering front spread upward, and T1–T3 reached the peak temperature successively. When the air flux was 0.8 m³/h, the smoldering reaction was intense due to sufficient air supply, and T1–T3 reached its peak temperature almost at the same time. Collapse occurred during the reaction, and the smoldering reaction mainly occurred at the bottom of the reactor, so the temperature of T3 was lower.

The experimental results are shown in Table 5. With the increase of air flux, the total smoldering time of corn straw powder decreased. Increasing the air flux provided sufficient air supply and further intensified the smoldering reaction, so the total reaction time decreased. When the air flux was 0.2 and 0.4 m³/h, the gas velocity had little influence on the peak temperature, and the smoldering peak temperature of corn straw was around 500 °C. When the air flux was 0.8 m³/h, due to sufficient oxygen supply, the reaction was more intense, the peak temperature of T1 was higher, and collapse occurred during the reaction. On measuring the gas temperature, the peak temperature of T3 was significantly lower than T1 and T2.

The smoldering propagation velocity of corn straw powder under different air fluxes is shown in Table 6. Because the collapse occurred in the third experiment, no calculation was done. The propagation velocity of the drying front and the carbon oxidation front increased with the air flux. The increased air flux took away more moisture, and the moisture was easier to evaporate. Meanwhile, the increased air flux increased the oxygen supply, the smoldering reaction speeded up, and the propagation velocity of the carbon oxidation front increased.

5.4. Variation of Bed Temperature with Air Flux. When the stacking density was 71.11 kg/m³ and the air flux was 0.2, 0.4, and 0.8 m³/h, the temperature change of T1-T3 was simulated by COMSOL, as shown in Figure 8. The heat transfer velocity and the bed temperature increased with the air flux, the maximum difference of the bed temperatures was about 50 °C. Increasing the air flux intensified the convective heat transfer coefficient between the solid particles and the gas. The peak temperature of each point increased with the air velocity, because the time for the air to pass through the porous media became shorter, the heat transfer time decreased, the total convective heat transfer between solid particles and gas decreased, and the bed temperature increased. Increasing the air velocity increased the convective heat transfer between solid particles and gas in unit time, but shortened the convective heat transfer time. Therefore, the influence of air flux on combustible particles should be analyzed combining with the actual situation.

At an air flux of 0.2, 0.4, and 0.8 m³/h, the temperature profiles of T1 at different stacking densities are shown in Figure 9. When the air flux was 0.2 m³/h, the peak temperature was higher under the condition of smaller stacking density. When the air flux was 0.4 and 0.8 m³/h, the peak temperature was higher under the condition of larger stacking density. The fluid passed through the solid particles for a long time at low air velocity, the two were in full contact, which was conducive to convective heat transfer. When the stacking density was large, there were more solid particles in unit volume, and the convective heat transfer was large, so the peak temperature of the bed was lower. However, at high air velocity, the fluid passed through the solid particles quickly and the convective heat transfer was small. When the stacking density was large, there were more

Table 5. Total Smoldering Time and Peak Temperature under Different Air Fluxes

| air flux (m³/h) | total smoldering time (h) | peak temperature (°C) |
|----------------|--------------------------|-----------------------|
|                | T1 | T2 | T3 |
| 0.2            | 6.66 | 514 | 515 | 518 |
| 0.4            | 6.45 | 500 | 496 | 485 |
| 0.8            | 6.05 | 560 | 508 | 324 |

Table 6. Smoldering Propagation Velocity under Different Air Fluxes

| gas velocity (m/s) | propagation velocity of the drying front (mm/h) | propagation velocity of the carbon oxidation front (mm/h) |
|--------------------|--------------------------------------------------|--------------------------------------------------------|
| T1–T2 | T2–T3 | T1–T2 | T2–T3 |
| 0.2   | 46.99 | 28.26 | 17.35 | 27.82 |
| 0.4   | 89.11 | 29.69 | 28.08 | 21.26 |
| 0.8   | 88.09 | 39.85 |              |
solid particles in unit volume, and the heat conduction was large, so the peak temperature of the bed was high.

5.5. Local Energy Analysis of Corn Straw Powder Smoldering. According to TG and DSC data, the reaction...
heat of corn straw powder in air and nitrogen was $-34.2917$ and $-3236.4072$ J/g, respectively. The heat released in the reaction zone under air and nitrogen conditions was calculated as two extreme values, and the local energy analysis was conducted to evaluate whether smoldering occurred and maintained. When the air flux was 0.2 m$^3$/h, 

Figure 10. Local energy analysis of corn straw powder smoldering under air condition for different stacking densities (the dotted line represents zero heat).

Figure 11. Local energy analysis of corn straw powder smoldering under nitrogen condition (the dotted line represents zero heat).
the bottom constant temperature was 300 °C after heating for 30 min under air condition. The local energy analysis of corn straw powder smoldering at different stacking densities is shown in Figure 10.

Except for experiment 2, after the electric heating tube stopped heating, the heat released in the smoldering front was greater than the heat removed by convective gas flow, the net heat rate was positive, the local energy balance was positive, and the smoldering was self-sustaining. In experiment 2, due to the low room temperature (12 °C), the temperature at the reactor bottom was low after the heating was stopped. At this time, the smoldering reaction did not occur or the reaction was slow. The heat removed by convective gas flow was greater than the heat released, the net heat rate was negative, and the local energy balance was positive. As the reaction continued, the heat production gradually increased. In each experiment, the net heat rate changed from negative to positive after 11.23, 34.83, 7.03, and 19.7 min, respectively, and the local energy balance also changed from negative to positive. At this time, smoldering was self-sustaining. Integrating the net heat rate over time, the net heat was greater than zero after 16.67, 49.73, 14.97, and 32.6 min in each experiment. As the temperature of the second experiment was low, the smoldering entered the self-sustaining state for a longer time. The smoldering of corn straw powder would occur even under hypoxic condition after the heating was stopped, and the smoldering was self-sustaining.

When the stacking density was 85.33 kg/m³, the bottom constant temperature was 300 °C, after heating for 30 min. The local energy analysis of corn straw powder smoldering under different air fluxes is shown in Figure 12. As shown in Figure 10c, when the air flux was 0.2 m³/h, under air condition, after the heating was stopped, the heat released was greater than the heat removed by convective gas flow, the net heat rate was positive, the local energy balance was positive, and the smoldering was self-sustaining. As shown in Figure 11c, under nitrogen condition, after the heating was stopped, the net heat rate changed from negative to positive after 7.03 min, and the smoldering entered a self-sustaining state. After 14.97 min, the net heat was greater than zero. When the air flux was 0.4 and 0.8 m³/h, more heat would be

The bottom constant temperature was 300 °C after heating for 30 min under air condition. The local energy analysis of corn straw powder smoldering at different stacking densities is shown in Figure 10.

Except for experiment 2, after the electric heating tube stopped heating, the heat released in the smoldering front was greater than the heat removed by convective gas flow, the net heat rate was positive, the local energy balance was positive, and the smoldering was self-sustaining. In experiment 2, due to the low room temperature (12 °C), the temperature at the reactor bottom was low after the heating was stopped. At this time, the smoldering reaction did not occur or the reaction was slow. The heat removed by convective gas flow was greater than the heat released, the net heat rate was negative, and the local energy balance was positive. After the electric heating tube stopped heating, the residual heat at the bottom continued to heat the corn straw powder, which increased the reaction zone temperature, intensified the smoldering reaction, and increased the heat production. After 12.66 min, the net heat rate changed from a negative to positive value. At this time, the local energy balance was positive and the smoldering was self-sustaining. After 17 min, the net heat was greater than zero. Therefore, under air condition, after the heating was stopped, a smoldering reaction occurred in the corn straw powder, and the smoldering was self-sustaining.

Under nitrogen condition, because of the absence of oxygen, corn straw powder pyrolysis and the reaction heat was small. The local energy analysis of corn straw powder smoldering at different stacking densities is shown in Figure 11. After the heating was stopped, the pyrolysis reaction began to take place, and the heat production was very little. In each experiment, the heat released in the smoldering front was less than the heat removed by convective gas flow, the net heat rate was negative, and the local energy balance was negative. As the reaction continued, the heat production gradually increased. In each experiment, the net heat rate changed from negative to positive after 11.23, 34.83, 7.03, and 19.7 min, respectively, and the local energy balance also changed from negative to positive. At this time, smoldering was self-sustaining. Integrating the net heat rate over time, the net heat was greater than zero after 16.67, 49.73, 14.97, and 32.6 min in each experiment. As the temperature of the second experiment was low, the smoldering entered the self-sustaining state for a longer time. The smoldering of corn straw powder would occur even under hypoxic condition after the heating was stopped, and the smoldering was self-sustaining.

When the stacking density was 85.33 kg/m³, the bottom constant temperature was 300 °C, after heating for 30 min. The local energy analysis of corn straw powder smoldering under different air fluxes is shown in Figure 12. As shown in Figure 10c, when the air flux was 0.2 m³/h, under air condition, after the heating was stopped, the heat released was greater than the heat removed by convective gas flow, the net heat rate was positive, the local energy balance was positive, and the smoldering was self-sustaining. As shown in Figure 11c, under nitrogen condition, after the heating was stopped, the net heat rate changed from negative to positive after 7.03 min, and the smoldering entered a self-sustaining state. After 14.97 min, the net heat was greater than zero. When the air flux was 0.4 and 0.8 m³/h, more heat would be
taken away due to the increase of wind speed. After the heating was stopped, the reaction zone temperature was low, the heat released was less than the heat removed by convective gas flow, the net heat rate was negative, and the local energy balance was negative. As the reaction zone temperature continued to rise, the smoldering reaction was gradually accelerated. Under air condition, the net heat rate converted to a positive value after 10.9 and 10.93 min. Under nitrogen condition, the net heat rate converted to positive after 33.53 and 32.8 min. At this time, the local energy balance was positive, there was energy accumulation and the smoldering was self-sustaining. Under air condition, the net heat was greater than zero after 15.03 and 14.33 min. Under nitrogen condition, the net heat was greater than zero after 49.26 and 49.46 min. Although the heat was removed more when the wind speed was high, the oxygen supply was sufficient, which was conducive to the smoldering reaction. Therefore, when the air flux was 0.8 m$^3$/h, the smoldering entered the self-sustaining state first.

When the air flux was 0.2 m$^3$/h, the bottom constant temperature was 150 °C and the stacking density was 71.11 and 85.33 kg/m$^3$, after heating for 30 min. The bed temperature change is shown in Figure 13. After the electric heating tube stopped heating, the energy analysis of the reaction zone is shown in Figure 14. After the heating was stopped, the temperature at the bottom was low, the smoldering reaction did not occur, and the heat production was zero. The gas removed some of the heat, so the net heat rate was negative and the local energy balance was negative. As the temperature of corn straw powder decreased, the heat removed by gas flow decreased, and the net heat rate gradually approached zero. Under air and nitrogen conditions, the corn straw powder was not ignited after heating, and the smoldering reaction did not occur after a period of time.

6. CONCLUSIONS

The influence of stacking and ventilation characteristics on the smoldering propagation process was studied to provide guidance for the safe storage of biomass pellets. The effects of stacking density and air flux on the smoldering propagation process were studied experimentally, the variation of bed temperature with stacking density and air flux was analyzed using the numerical simulation technique, and the conditions of self-sustaining smoldering were determined by the local energy analysis method. After ignition, the temperature rose slightly and then entered a plateau. At this time, the moisture evaporated. When the water completely evaporated, the corn straw powder began to oxidize and heat up rapidly. The peak smoldering temperature of corn straw powder was between 500 and 520 °C, and the smoldering propagation velocity was between 10 and 30 mm/h. When the stacking density was changed in the range of 56.89–99.56 kg/m$^3$, the change in the rate of the peak smoldering temperature was about 2%. The smoldering propagation velocity decreased with the increase in stacking density and the decrease amplitude was up to 30%. With the increase in the stacking density, the smoldering propagation velocity decreased. The higher the stacking density, the slower the heat transfer and the lower the bed temperature within the same time, and the maximum difference can be about 10 °C. Although oxygen supply was restricted at this time, heat loss was also hindered, which increased the risk of smoldering.

When the air flux was 0.2 and 0.4 m$^3$/h, it had little effect on the peak smoldering temperature. Also, when the air flux was 0.8 m$^3$/h, the peak smoldering temperature was higher, which can reach 560 °C. The smoldering propagation velocity increased with the increase in air flux, and the increase rate was up to 60%. At this time, the oxygen supply was sufficient and the smoldering reaction would accelerate. The higher the air flux, the faster the heat transfer and the lower the bed temperature within the same time, and the maximum difference can be about 50 °C. The increase in air flux increased the convective heat transfer between solid particles and gas in unit time but shortened the convective heat transfer time. Therefore, the influence of air flux on the smoldering of combustible particles needed to be analyzed in combination with the actual situation.

Furthermore, the local energy analysis of the smoldering front was performed based on TG and DSC data. After the ignition, smoldering occurred in all the experiments under different stacking densities and air fluxes, and smoldering could be self-sustaining after a period of time. When the air flux was 0.2 m$^3$/h, the bottom constant temperature was 150 °C; after heating for 20 min, the corn stalk powder was not ignited under air and nitrogen conditions, and the smoldering reaction did not occur after a period of time. The results showed that when the heat released in the smoldering front was greater than the heat removed by convective gas flow, the net heat rate was positive. At this time, the local energy balance was positive, there was energy accumulation in the system, the smoldering was self-sustaining, and the smolder-
ing front propagated from the bottom to top. When the heat released in the smoldering front was less than the heat removed by convective gas flow, the net heat rate was negative. At this time, the local energy balance was negative and smoldering could not occur. We hope that this work will provide data support for safety in the storage and production of biomass pellets.

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**Notes**

The authors declare no competing financial interest.

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