The Defluidization during Rubber Wood Combustion in Fluidized Bed

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Abstract – The defluidization behaviors were investigated experimentally when the rubber wood was burning tested in a laboratory scale fluidized bed reactor. The focuses of this work were the behaviors of fluidized bed during the combustion and the effects of operating conditions, including bed temperature, air velocity and bed particle size, on the bed agglomeration tendency. It was found that the defluidization caused by the bed particle agglomeration was clearly detectable from the decrease in measured bed pressure. The growth of particles in bed and accumulation of agglomerates during combustion led the bed to complete defluidization. The defluidization was promoted by the increase of bed temperature and bed particle size, and the decrease of fluidizing air velocity.

Keywords – Bed agglomeration, defluidization, fluidized bed combustion, rubber wood.

1. INTRODUCTION

Fluidized bed combustion (FBC) is well known as a thermo-chemical conversion technique of solid fuels to achieve high combustion efficiency with low emission, high heat transfer rate, and high fuel flexibility [1], which have been exploited with biomass. It is particularly due to good gas-solid contact and large contact surface area, resulted from chaotic solid bed mixing by upward flowing gas stream [2].However, the agglomeration of bed particles is a greatest problem in FBC of solid fuels, especially derived from agricultural residues. This phenomenon affects negatively fluidization and even shuts down fluidized bed, namely defluidization [3].

Biomass fuels from agricultural residues generally contained inorganic constituents that were able to form liquid substances during combustion [4-5]. In the view point of bed agglomeration, alkali potassium, refractory silicon, alkali earth calcium and non-metallic chlorine, sulfur and phosphorus were important elements since they formed low melting point compounds which their liquid phase presented in agglomerates as adhesive material, in form of bonding bridge and coating [5-6]. Once agglomerates were formed and overcame the breaking induced by the collision of particles in fluidized bed, defluidization began.

A number of previously studies [5-7] revealed that bed agglomeration was mainly attributed to the inorganic compositions of fuel. The tendency of bed agglomeration was a strong function to the contents of potassium, calcium, silicon, chlorine and sulfur in fuels. Additionally, the operation of fluidized bed also affected the tendency [8].As mentioned, the bed agglomeration affected the bed hydrodynamic described by the deviations of bed pressure and bed temperature [9]. It included the decrease or fluctuation of whole/local bed pressure and non-uniform bed temperatures. Agglomerated bed particles were formed earlier before the deviations were detected [10]. Several monitoring and warning methods were therefore developed by mathematical analyses of the bed pressure data to early detect incipient bed agglomeration, for reduction in the risk for agglomeration in bed [11]-[12].

In order to gain more understanding in the effects of bed particle agglomeration to fluidization behaviors, the present study aimed to investigate the fluidized bed behaviors during the combustion and the effects of bed operating variables on the bed agglomeration tendency during the combustion of rubber wood in a fluidized bed reactor.

2. EXPERIMENTAL SET UP

2.1 Biomass and Bed Particle

The biomass fuel selected for this study was rubber wood. In Thailand, rubber wood which obtains from replantation for aged rubber tree (*the decline in latex production makes further tapping of the trees uneconomic after approximately 30 years of age*) is widely used, for instance; furniture, construction wood and the raw material of cooking charcoal, activated carbon and fuel wood pellet [13].Rubber wood chipped is also used as fuel to mainly produce steam in latex factories. Rubber woodchip is considered suitable for use as a solid fuel to generate heat and/or power due to its relatively high bulk density and uniform shape and size.

The combustion properties of the rubber woodchip, received, and its ash compositions were reported in Tables 1 and 2, respectively. The woodchip contained the large volatile substance, low fixed carbon, as typical biomass fuel. It also had the low chlorine and sulfur contents. Calcium was rich in the biomass ash, expressed as oxide form, while silicon was relatively poor. The potassium content in the fuels was relatively high. According to the property data, the fluidization during the rubber wood combustion was expected to be problematic to some extent due to the potassium content.

The bed particle used for the experiment was silica sand. Its chemical properties analyzed by X-ray

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fluorescent (XRF) and X-ray diffraction (XRD) were given in Table 3, expressed as oxide form. The bed material was assertive SiO_2 compound in the hexagonal crystalline structure, and the small amounts of mineral impurities. The bed of the sand had initially the narrow particle size distributions, as shown in Figure 1, which employed in 3 adopted size ranges. The calculated minimum fluidization velocities (U_{mf}) of each size ranges at observed bed temperature were 0.033 (268 μm), 0.05 (324 μm) and 0.07 (387 μm) m/s, respectively.

Table 1. Detailed properties of the rubber woodchip.

Proximate analyses[1] (*ASTM E870-82(2006)*)	Content (wt%)
Moisture	39.43 (6.7[2])
Volatile matter	49.64
Fixed carbon	9.22
Ash	1.71
Ultimate analyses[3]	
Carbon	48.78
Hydrogen	6.38
Oxygen[4]	41.68
Nitrogen	0.17
Sulfur	0.16
Chlorine (*ASTM E776-87(2004)*)	0.01

1: as received basis, 2: as fires basis, 3: as dry basis; 4: determined by difference

Table 2. The woodchip ash composition.

Inorganic element	Content (wt%)
SiO_2	4.06
Al_2O_3	0.67
CaO	51.69
MgO	8.05
Na_2O	0.44
K_2O	21.9
P_2O_5	2.67
Fe_2O_3	1.45
SO_3	3.05
Cl	0.29
Other	5.73

Table 3. The properties of silica sand.

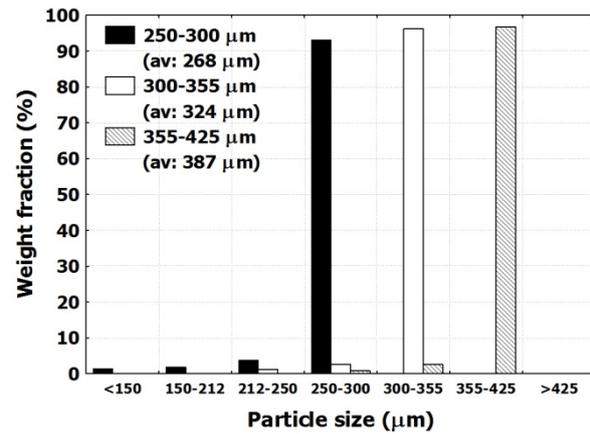| Crystalline structure	Hexagonal
Inorganic element	Content (wt%)
SiO_2	99.55
Al_2O_3	0.16
CaO	0.02
MgO	0.008
Fe_2O_3	0.05
Other	0.212

Fig. 1. Size distributions of the fresh bed.

2.2 Apparatus

The experiment was carried out in a laboratory scale bubbling fluidized bed reactor, schematically illustrated in Figure 2. The reactor was made of a stainless steel cylindrical tube with 8.4 cm. ID and 1.8 m. height. It was placed in an electrical tube furnace used to preheat the bed during startup. An air distributor was made of a perforated stainless circular plate with triangular pitch of 0.6 mm. drilled holes, approximately 1% of total opening area. The fluidizing air produced from an air compressor and reduced to 1 bar g by an air regulator was preheated and introduced into the bed through a perforated stainless steel plate distributor. In the wind-box, twisted stainless steel strips were packed for 0.7 m height to serve as an air pre-heater, 30 cm. beneath the bed. The air flow rate was measured by a calibrated orifice. At the top of the reactor, the fuel was stored in a container and continuously fed over the bed by a frequency adjustable shaker. The pressure and temperature of the bed were measured continuously by a differential pressure transmitter, which its probe was located in the bed at the air distributor relative to atmospheric pressure (whole bed pressure), and two K-type thermocouples, placed at 1 and 3 cm. above the air distributor and 1 cm. away from the reactor wall, respectively. The bed pressure and bed temperature profiles, as well as the air flow, were monitored and logged on a PC via a data acquisition unit.

When bed was partially defluidized, bed temperature profiles were not homogeneous due to poor bed mixing and bed pressure was reduced by the creation of gas channels within bed, namely bed channeling [14].
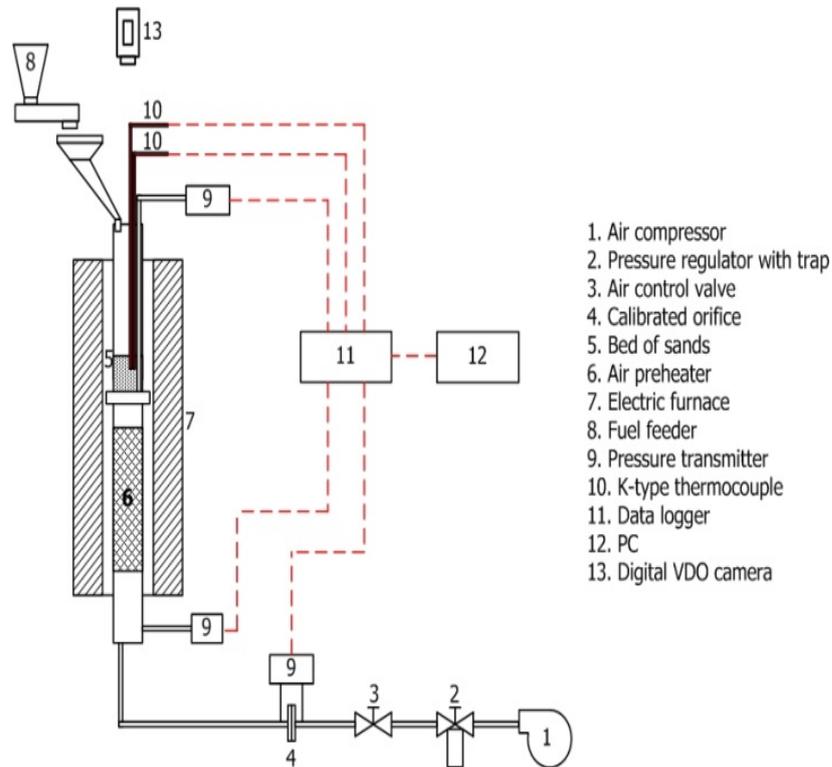
1. Air compressor
2. Pressure regulator with trap
3. Air control valve
4. Calibrated orifice
5. Bed of sands
6. Air preheater
7. Electric furnace
8. Fuel feeder
9. Pressure transmitter
10. K-type thermocouple
11. Data logger
12. PC
13. Digital VDO camera

Fig. 2. Schematic diagram of the lab scale apparatus.

2.3 Fuel Preparation

The woodchip received had high in the moisture content, as shown in Table 1, and had 3-7 cm. in size, which was too large to be fed by the existing feeder. The woodchip was first dried in open air to remove excess water (to 6.7%, as fired basis). Subsequently, it was introduced to a small hammer mill and then sieved to 0.8-1.2 cm of adopted size range, in order to be fed uninterruptedly.

2.4 Bed Agglomeration Test

The effects of bed temperature (T_b), fluidizing air velocity (U) and bed particle size (d_p) on the bed agglomeration tendency were studied under atmospheric combustion. The controlled conditions of the fluidized bed were summarized in Table 4. The static bed height to bed diameter ratio (H_b/D_b) of the bed was set at 0.5. The operational air velocity given was varied in the range of 3-6 times of U_{mf}, which was in the early state of aggregative fluidization (*the beginning of bubbling regime to the end of turbulent regime*) [2].

Table 4.Experimental conditions

Parameter	Observed range
Bed temperature (°C)	850-950
Air velocity (m/s)	0.15-0.25
Bed particle size (μm)	250-425

When the bed was filled in the reactor and was first heated up to a certain temperature, it was fluidized at the required air velocity which was maintained over the trial. The required bed temperature was thence reached by subsequent combustion of the fuel, and the furnace was then switched off. The observed bed temperature was maintained over the trial by the control of biomass feed rate. The recorded time started as the fuel feeding began. During the trial, the bed pressure and bed temperature profiles were monitored, and the combustion and fluidization behaviors were visually observed at the reactor's top view (by a digital video camera, which recorded for several short time intervals throughout the trial).The trial eventually ended when the bed was completely defluidized, and the fuel consumption obtained from the initial and final weights of the fuel batch was recorded. After defluidization, the bed cooled and discharged was sieved to analyze the particle size distribution, and to separate the agglomerates. Several conditions were repeated twice in order to test the reproducibility.

3. RESULT AND DISCUSSION

3.1 Bed Behaviors

The typical bed behaviors during the combustion at a condition were shown in Figure 3. The baseline and fluctuation amplitude of the bed pressure, about 4 mbar at initial combustion, decreased gradually until complete defluidization at 1,028 sec while the bed temperatures showed relatively uniform and constant (Figure 3a).The agglomerates found were formed in various sizes and easily breakable (Figure 3b). The increase of the bed particle size was showed (Figure 3c), although it was likely affected by the breaking of the agglomerates during discharge and sieving. The weight loss of the bed after defluidization at the typical condition was slightly, approximately 0.33% of the fresh bed.
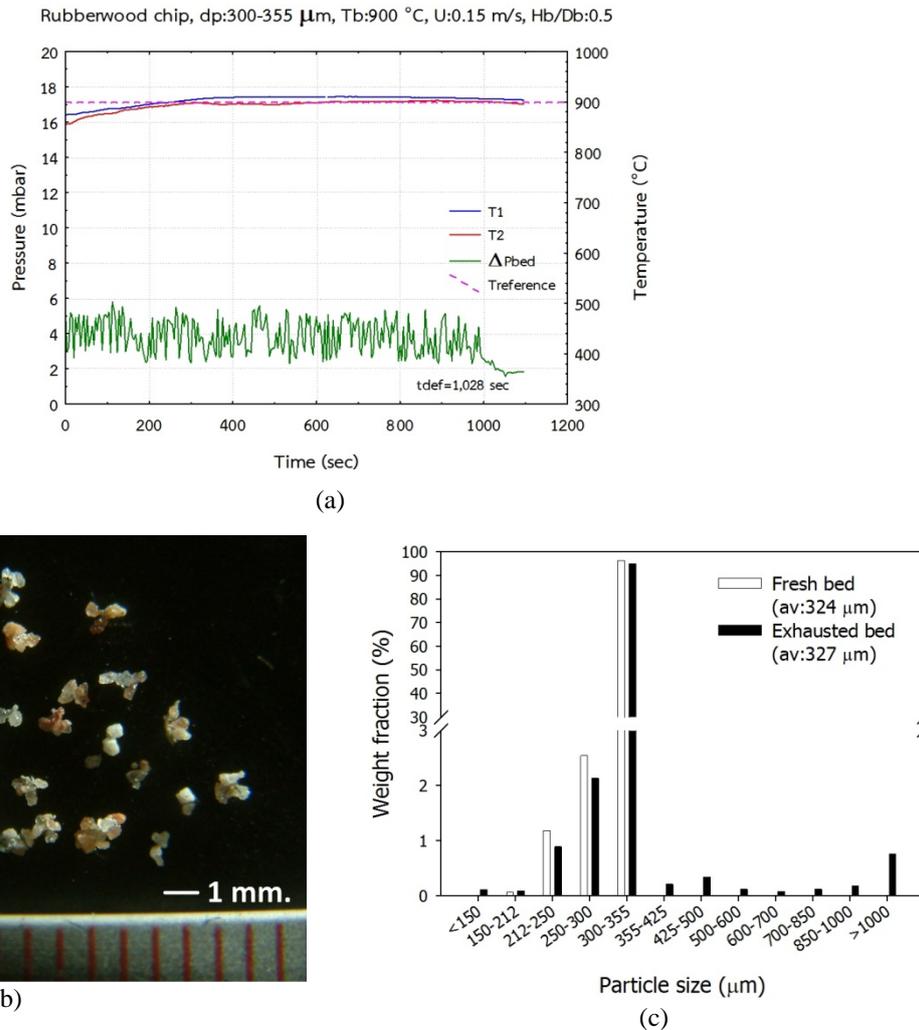
(a)

(b)

(c)

**Fig. 3. Typical bed behaviors during the combustion; (a) The bed pressure and bed temperature profiles,
(b) The agglomerates and (c) the particle size distribution of the fresh and exhausted beds.**

The above results were connected significantly to the alteration of bed hydrodynamics during combustion. The growth of the bed particles due to the agglomeration and the accumulation of the agglomerates established the more multi size particles in the bed. It essentially induced increasing bed void fraction, namely bed channeling [3], and subsequently decreasing fluid flow resistance through bed [2] which was indicated by the decrease of bed pressure and fluctuation amplitude. The fluctuation of bed pressure originated from the passage of bubbles between pressure probe and downwards propagating pressure wave formed by erupting bubbles at bed surface [15]. The decreasing amplitude reflected the decreasing size of bubbles passing through bed [16], as a consequence. In addition, bed agglomeration further induced subsequent poor bed mixing which caused segregate combustion zone in bed, reported as non homogeneous bed temperature profiles [3], [5], [6], [14]. However, the bed temperature profiles in this work showed opposite behavior. It was probably due to that no hot spots, as segregate combustion zone, randomly took place near the thermocouples during the combustion.

In this study, the segregation of measured bed temperatures, which was another indicator of defluidization [12], [14], was not clearly observed and the presence of defluidization was more clearly detectable from pressure measurement. As agglomerates began to be formed, bed started to be defluidized, and their accumulation caused bed to progressively reach complete defluidization. In fluidization fundamental, the increase in bed particle size translated into greater U_{mf}. As a result, superficial gas velocity had to be increased in order to maintain the fluidization state. If it was not increased accordingly, or whole bed agglomerated in extreme case, fluidization could no longer be maintained. The slightly lost weight of the bed after defluidization (0.22-0.36% of the fresh bed at the observed conditions) was probably due to the elutriation of fine particles/bed particles generated from the collision/attrition of particles in fluidized bed, as well as loss during discharge.

3.2 Bed Agglomeration Tendency

The results of the bed agglomeration test were reported in term of defluidization time (t_{def}). It was defined as the time interval between the start of the fuel feeding and the complete defluidization. The bed agglomeration tendency was described in inverse to its value; the lower t_{def}, the higher the tendency. The influences of the operating

parameters on t_{def} were shown in Figure 4. In addition, the results of the repeated experiments were summarized in Table 5. They showed a fairly good reproducibility with respect to t_{def}.
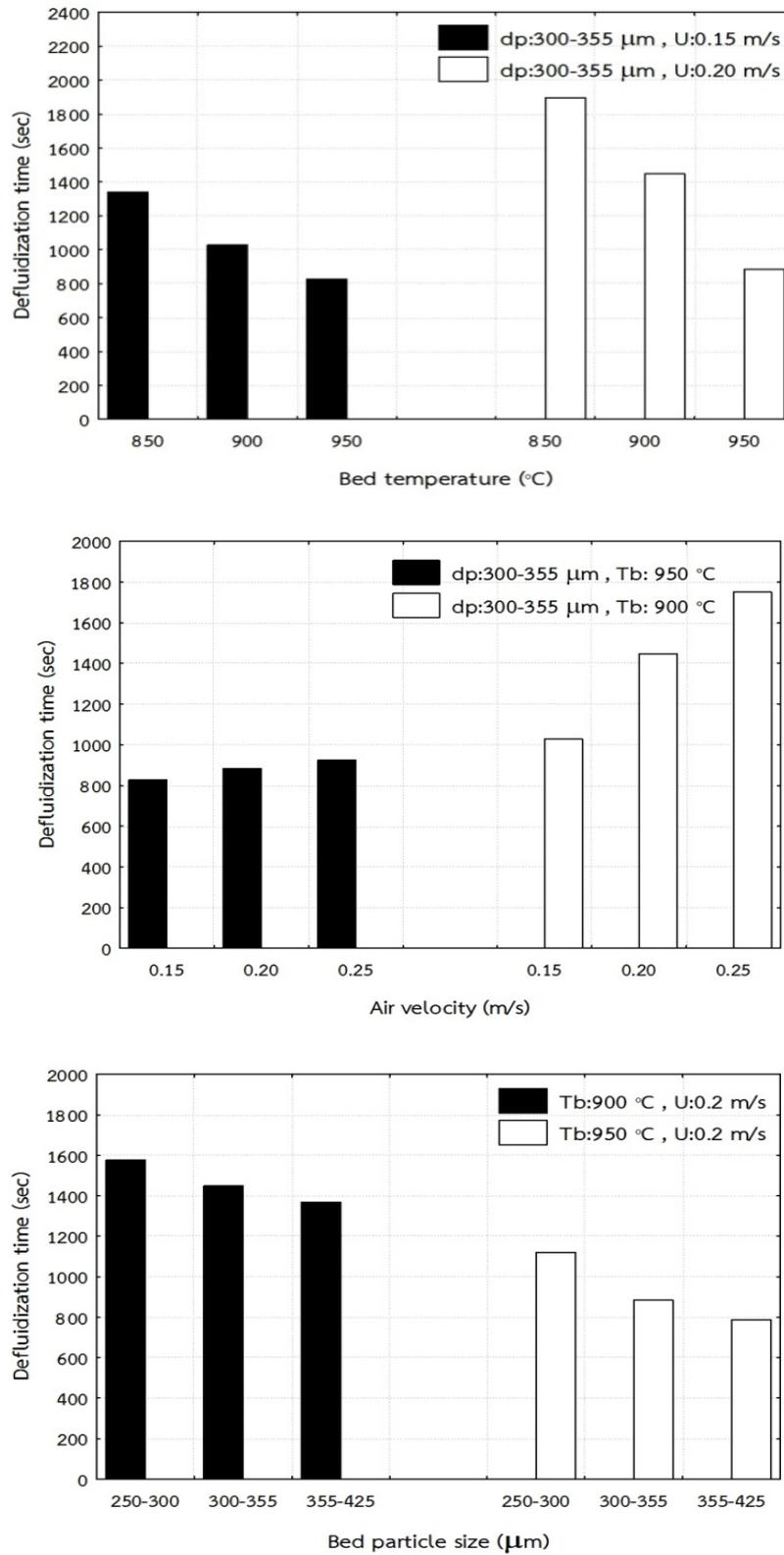

Fig. 4. The effects of controlled operating variables on the bed agglomeration tendency; (a) bed temperature, (b) air velocity and (c) bed particle size.

3.2.1 Effect of bed temperature

Defluidization time (t_{def}) as a function of bed temperature was shown in Figure 4a. The bed reached faster to the complete defluidization as the bed temperature increased. As temperature that exceeds the initial melting point of ash forming compounds increased, the fraction of ash melt increased [17] and the viscosity of the melt decreased resulting to increase adhesion efficiency [18]. The combination of these two factors facilitated the agglomeration of bed particles coated and glued together by molten compounds. This accelerated defluidization.

3.2.2 Effect of air velocity

As shown in Figure 4b, t_{def} was extended as the air velocity increased. The higher air velocity in bed resulted to increase the mobility of bed particles, as intensified bed mixing, and raise resultantly the forces of attrition and breaking, induced by bubbles, acting on agglomerates [19], [20]. This delayed defluidization and the amount of ash necessary to defluidize bed was higher from more fuel consumption to form/consolidate agglomerates in enhanced fluidization.

3.2.3 Effect of bed particle size

At the same bed temperature and air velocity, the increase of the bed particle size reduced t_{def} as shown in Figure 4c. Because the bed of larger particles had lower specific surface area, lesser molten ash to form coating/bonding layers was necessary for agglomeration. In addition, U_{mf} of larger particles was higher. Therefore, the bed mixing would not be as good as that of smaller particles at the same air velocity, as the ratio of U/U_{mf} was lower. This feature easily caused segregate combustion zone and hot spots in bed, which enhance the formation of ash melt. These two factors accelerated defluidization for larger bed particles.

In this study, t_{def} showed a good indicator to describe the bed agglomeration tendency. Defluidization was a result of competition between the adhesion of bed particles, which arise from molten ash formation and sintering, and the breaking of agglomerated particles, induced by fluidization. It took place rapidly as the former was enhanced by the increasing accumulation rate of alkali in dense bed, increasing bed temperature, or otherwise the latter was worsened by some conditions leading to poor bed mixing.

This present study showed the physical behaviors of the defluidization which was impacted by the agglomeration of bed particles. The morphological and chemical studies of the agglomerates were then carried out in the further experiment, in order to elucidate the behaviors of fuel inorganic elements during combustion and the governing processes of bed agglomeration. The present work is a case study of bed agglomeration and more experimental works carried out with various biomasses are required to investigate and confirm the behaviors of bed agglomeration and defluidization. It is necessary in order to verify the recently developed mathematical model to obtain more accurate prediction in the behaviors of bed agglomeration.

4. CONCLUSION

The presence of the defluidization due to the bed agglomeration is marked by the decrease of bed pressure drop. It was clearly detectable from the bed pressure measurement. The bed suffered the complete defluidization because of the growth of the bed particles and the accumulation of the agglomerates.

The increase of bed temperature and bed particle size, and the decrease of air velocity promoted the defluidization.

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