Flow behavior in an agglomerated fluidized bed gasifier

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Abstract

The global energy demand has increased over the last decades, and the need for utilization of energy produced from renewable sources is stressed. Fluidized bed gasification of biomass is a sucessful technology for a sustainable energy conversion process. Agglomeration of bed material is one of the biggest challenges associated with fluidized bed gasification of biomass. Inorganic alkali components from the biomass cause problems as they melt and form a sticky layer on the surface of the bed particles, forming agglomerates that will interfere with the fluidization process. In the present work, the effect of agglomerates on the flow behavior in a fluidized bed gasifier was studied. The experiments were performed in a cold-flow model of a bubbling fluidized bed at ambient temperature. The results show that agglomerates lead to decreased pressure drop and increased minimum fluidization velocity. The minimum fluidization velocity increased from 0.035 m/s in the normal fluidized bed to 0.041 m/s in the agglomerated fluidized bed where the agglomerates were placed at the bottom of the bed. The minimum fluidization velocity increased further to 0.057 m/s in the agglomerated fluidized bed where the agglomerates where added from the top of the bed. This study also found that bed agglomeration causes channeling and poor fluidization conditions.

Keywords: biomass gasification, fluidized bed gasification, fluidization, agglomeration

1. Introduction

In order to limit the earth's global warming due to increased CO_2-emissions, there is an urgent need to promote the use of sustainable alternatives to fossil fuels. Among all the renewable resources, biomass is considered the most important source for sustainable energy production. [1] One of the promising energy conversion technologies for biomass is fluidized bed gasification, which converts the biomass into a gaseous mixture of syngas in presence of heat and a gasifying agent [2]. The syngas consists of mainly hydrogen (H_2) and carbon monoxide (CO), which can be further converted into biofuels [3]. Fluidized bed conversion is the leading technology for utilization of a broad variety of solid fuels, and is proved particularly advantageous for biomass gasification technology [4]. In addition to their fuel flexibility, fluidized bed gasifiers are noted for their uniform heating, excellent heat transfer, high efficiency and low environmental impact. Despite the advantages with fluidized bed technology, some difficulties appear during the thermochemical conversion of biomass-derived fuels. Ash-related problems are the main obstacles for successful applications of fluidized bed gasification of biomass. [3] The major challenge associated with the ash produced in the gasification reactor is the formation of melted ash, which forms agglomerates that deposit at high temperatures. Bed agglomeration decreases both the heat transfer in the bed and the fluidization quality, resulting in poor conversion efficiencies and loss of control of the bed operation parameters. In the most severe cases, bed agglomeration can lead to total de-fluidization of the bed material [2]. The objective of this work is to study the effect of bed agglomeration on the flow behavior in fluidized bed gasification of biomass. In the present study, sand particles with a mean diameter of 175 μm are used as bed material. The experiments are carried out in a cold flow model of a bubbling fluidized bed. The minimum fluidization velocity is measured from the pressure drop in the bed at different superficial velocities. Bubble behavior in the bed is observed to study the fluidization characteristics of the bed material in an agglomerated fluidized bed.

2. Theory

1.2 Fluidization theory

Fluidization is the phenomenon in which solid particles are kept in a fluidized state by passing a gasifying medium through at an appropriate temperature. The gasifying medium can be steam, air or oxygen. [6] At a very low superficial velocity, the frictional force (drag) between the particles and the gasifying medium is too weak to suspend the particles, and the fluid passes straight through the void spaces between the particles. In this condition, the bed essentially remains fixed and the pressure drop in the bed is given by Ergun's equation. [7] As the superficial velocity is steadily increased, the bed expands slightly. The drag increases and at some point the particles begin to move. At a certain velocity, the upward-flowing fluid will suspend the particles. [8] This state is referred to as the minimum fluidization and the corresponding superficial velocity is the minimum fluidization velocity. In this condition, the suspended particles exhibit fluid-like properties. The minimum fluidization velocity is useful as a rough indication of the quality of the fluidization, and is an important parameter required for the design and operation of a fluidized bed.

The minimum fluidization velocity can be found both theoretically and experimentally. In fluidized state, the pressure drop through any section of the fluidized bed is equivalent to the weight of the solid particles per unit area, and the minimum fluidization velocity is determined based on [8]

$$\underbrace{g(1-\varepsilon_{mf})(\rho_s-\rho_f)}_{\text{Weight of particles}} = \underbrace{150\frac{u_{mf}\mu_f}{(\varphi_s d_p)^2}\cdot\frac{(1-\varepsilon_{mf})^2}{\varepsilon_{mf}{}^3} + 1.75\frac{u_f^2\rho_f}{\varphi_s d_p}\cdot\frac{(1-\varepsilon_{mf})}{\varepsilon_{mf}{}^3}}_{\text{Drag force by upward moving fluid}} \qquad 1\text{-}1$$

Where ε_{mf} indicates the bed voids at minimum fluidization condition, ρ_f is the density of the fluid and ρ_s is the density of the bed material. u_{mf} is the superficial velocity at minimum fluidization, μ_f is the viscosity of the fluid, φ_s is the sphericity of the solid particles and d_p is the particle diameter.

For fluidization of small particles where Reynolds number is less than 20, the viscous drag force dominate the process. In such cases, the mathematically expression of the minimum fluidization velocity is simplified to [8]

$$u_{mf} = \frac{d_p^2(\rho_p-\rho_f)g}{150\mu_f}\cdot\frac{\varepsilon_{mf}^3\varphi_s^2}{1-\varepsilon_{mf}}, \qquad Re_{mf} < 20 \qquad 1\text{-}2$$

Where Re_{mf} refers to Reynolds number.

Experimentally, the minimum fluidization velocity is determined by measuring the pressure drop in the bed at different superficial velocities. The data are plotted in a curve similar to Figure 1, u_{mf} is defined as the point at the boundary between fixed and fluidized conditions.

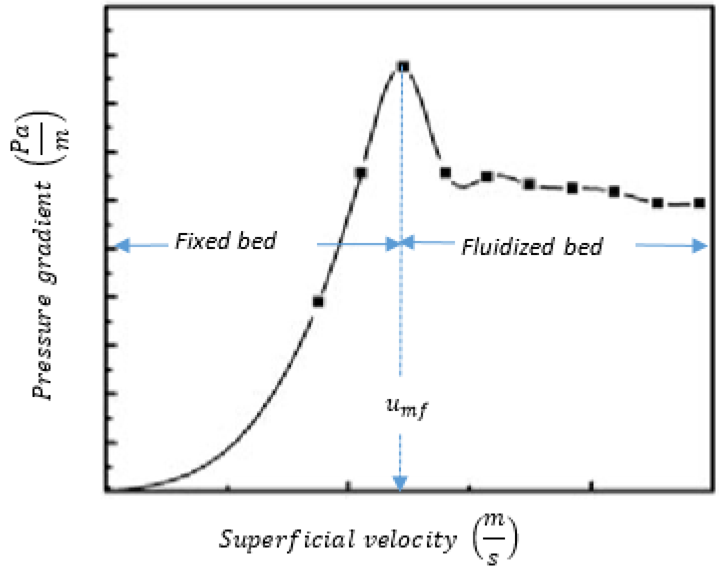

Figure 1. Pressure drop versus minimum fluidization velocity. [10]

As the velocity increases above u_{mf}, bubbles begin to form and the bed becomes fluidized. The formation of bubbles in the fluidized bed depends on properties of the particles such as size, size distribution and density. [9, 11]. Geldart classified particles into four types: A, B, C and D based on their fluidization behavior and mapped the particle types by its size and density in a diagram [12]
In this study Group B particles are investigated, they are characterized by fluidizing easily due to good mixing of the particles in the bed. At the onset of fluidization, bubbles are formed. [8, 12].

1.3 Bed agglomeration

Despite the widespread use of fluidized beds, the gasification process of biomass still has some difficulties [5]. The main problem is the melting, or the partial melting, of ash components that forms agglomerates, meaning the ash components adhere to eachother to form larger entities. [12]

During biomass gasification, inorganic alkaline components from the fuel can interact with silica from the bed material to form low-melting silicates that coat the bed particles [12]. If the alkali content is high enough, the coating melts and binds the bed particles together. Figure 2 illustrates how alkali-melt compounds contributes to the agglomeration process in a bubbling fluidized bed. The phenomenon occurs due to chemical reactions and physical collisions between the bed materials and the alkaline ash components. A consequence of the collisions is attachment of ash particles on the bed particles, resulting in formation of an adhesive and porous ash layer on the surface of the bed materials. As the ash particles and the bed materials continue to collide, the ash coating grow thicker. Eventually, the bed particles grow towards larger agglomerates that will interfere with the fluidization process. The agglomerates will become too large to be fluidized, and consequently they will stick to the walls or sink to the bottom of the bed and thereby prevent the fluid to pass freely through. [12, 13]

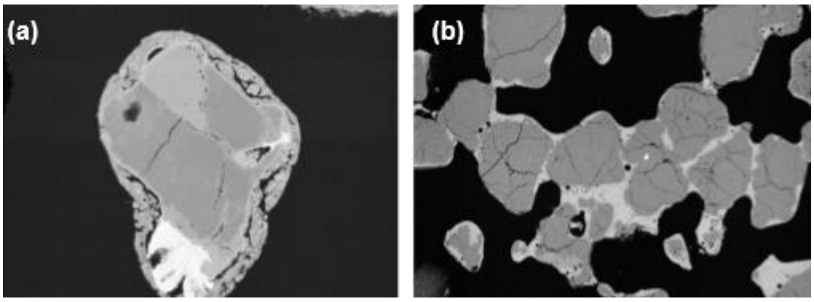

Figure 2. (a) silica sand particle surrounded by an alkali layer, (b) agglomerate formation. [12]

Smooth fluidization is essential for efficient and effective operation of the bed as it ensures good contact between the particles, hence optimal heat transfer in the bed. Due to the distinctive shapes, sizes and densities, agglomerates are difficult to fluidize adequately. Figure 3 pictures the irregularity in structures and compositions of agglomerates. The sticky and cohesive particles forms small volumes in the bed that are not completely fluidized. These de-fluidized volumes will have decreased heat transfer leading to overall increased temperatures in the bed. Moreover, higher temperatures will increase the stickiness of the particle surfaces resulting in increased de-fluidized volume in the bed. Eventually, the bed takes a sluggish appearance. The unwanted collapse of the fluidized bed is rarely recognized until sudden de-fluidization occurs and often leads to shutdown of the whole installation. [12]

Figure 3. Agglomeration of silica sand particles.

Agglomeration of bed material and ash sintering during fluidized bed gasification of biomass has been reported frequently in the literature. Pietsch [14] defined agglomeration as *"the formation of larger entities from particulate solids by sticking particles together by short range physical forces between the particles themselves, or through substances that adhere chemically or physically to the solid surface and form a material bridge between the particles"*.

Bartles et al. [12] presented an overview of research in the area of the mechanism of agglomeration. According to this review paper, there is agreement among researchers that the agglomeration process in fluidized bed gasifiers is a result of stickiness or adhesiveness of bed material produced by alkali compounds derived from the biomass ash. Siegill [15] and Squires [16] also describe that the de-fluidization phenomena is a direct consequence of stickiness. They claim that stickiness of bed material can be caused by changed properties of bed material at a certain temperature or due to presence of a liquid phase (melt) that deposit on the surface of the particles. [17]

Visser et al. [18] proposed two different routes for the initiation of the bed agglomeration: 1) 'melt-induced' agglomeration and 2) 'coating-induced' agglomeration. The 'melt-induced mechanism is direct adhesion of the bed particles caused by alkali compounds (molten ash) that acts as a glue, forming hard bridges between the particles. The 'coating-induced' mechanism refers to the formation of sticky uniform coating layers on the surface of the bed particles due to chemical reactions between the bed materials and the fluid phase.

Extensive studies performed on agglomeration in fluidized beds indicate that agglomeration and deposition leads to decreased pressure drop and instabilities with bubbling and channeling of gas. [8] Tardos and Pfeffer [19] stated that bed material agglomeration dramatically changes the fluidization behavior of a bubbling fluidized bed, thus the fluidization characteristics of the bed such as the minimum fluidization velocity, the pressure drop across the bed and the bubble behavior. Therefore, changes in bubble properties can be useful as an indication of agglomeration in fluidized beds. [5] The bubble frequency are defined as the number of bubbles passing through a specific area of the bed in a certain period of time. Under normal conditions, the bubble frequency through different sections along the bed are similar. When agglomeration occurs, the fluidization behavior changes and the bubble frequency through the different sections within the bed becomes different. During an experimental study of standard deviation of bubble frequency (STDBF), Montes [5] observed that the bed was channeling in some locations as illustrated in Figure 4. [5]

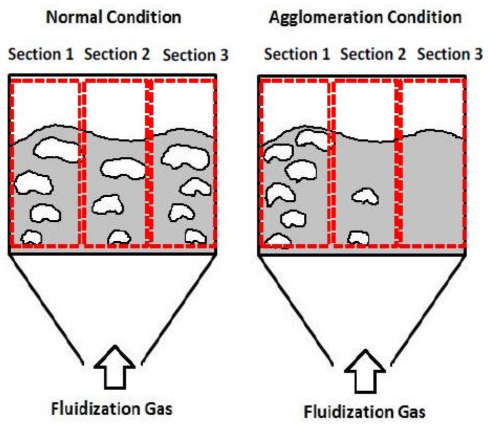

Figure 4. Bubble frequency in a fluidized bed [5]

One widely used experimental method to study the status of a bubbling fluidized bed is to measure the differential pressure. Under fluidized conditions, the pressure drop through the bed are equal to the total hydrostatic pressure of the bed. Due to channeling and agglomerated zones, agglomerated fluidized beds are characterized by lower pressure drop. [5]

2. Material and methods

The experiments were performed in the cold flow bubbling fluidized bed shown in Figure 5. The fluidized bed system consists of a column with height 140 cm and a diameter of 8.4 cm. The static bed height was approximately 21 cm. The gasifying medium was ambient air introduced into the bed through a porous plate distributor installed at the bottom of the column. The distributor ensures uniform air supply. The top of the column was open to the atmosphere. Nine pressure transducers along the height of the column were constantly monitoring the pressure drop across the bed. The pressure transducers were connected to the systems engineering software LabWiew for data acquisition.

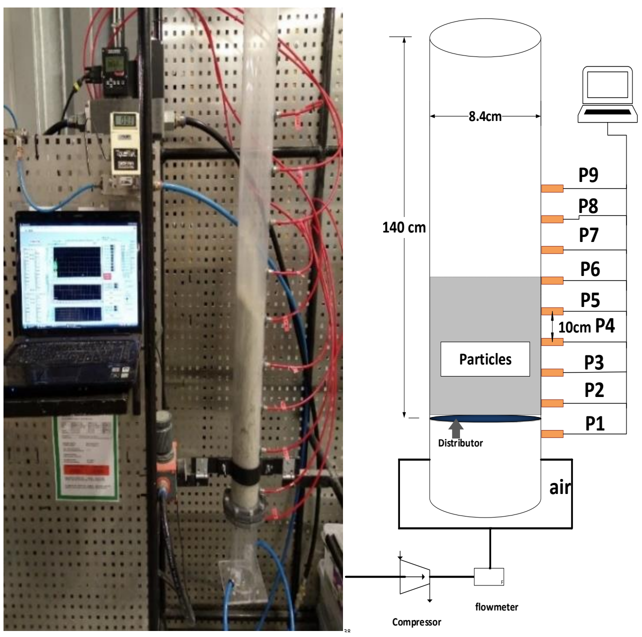

Figure 5. Cold flow model of bubbling fluidized bed.

The bed material used in the experiments were sand particles with a mean diameter of 175 μm and a bulk density of 1431 kg/m^3. According to Geldart fluidization diagram, the bed material corresponds to group B particles. The agglomerates are porous, which give them low density. As they consists of a large amount of primary particles clustered together, the agglomerates have completely random shapes and sizes and are therefore difficult to classify by Geldart diagram. [12] In the present experiments, the agglomerates varied from approximately 2 cm to 8 cm and density approximately equal to 1506 kg/m^3, as pictured in Figure 6. The agglomerates were weighed and the density was calculated based on mass and volume. The volumes of the agglomerates was found using a graduated cylinder. A precisely measured volume of sand particles was poured into the cylinder. The agglomerate was submerged in the sand, and the volume of sand displaced by the submerged agglomerate equals the volume of the agglomerate.

Figure 6. Agglomerates from fluidized bed gasification of biomass

Prior to the experiments, a sieving analysis of the sand particles was carried out and the mean diameter was determined from the mass fraction [20]. The bed material was weighed and the bulk density was calculated based on the mass and volume. The agglomerates were introduced to the bed together with the bed material and the superficial velocity (u_f) was gradually increased. The pressure drop in the bed (Δp_{bed}) was measured at different u_f, and the bubble behavior was observed during the whole fluidization process. The experiments continued until slugging of the bed was observed. Three different cases of fluidization processes were carried out: (I) with bed material (II) with agglomerates added at the bottom of the bed and (III) with agglomerates added from the top of the bed. Detailed specifications for the experiments are listed in Table 1.

Table 1. Details for the performed experiments,

Experiment	Description	Particle size	Particle weight	Particle density
I	Bed material	175 μm	-	ρ_{Bulk} = 1431 kg/m^3
II	Agglomerates located at the bottom of the bed	Smallest ~2 cm Largest ~ 8 cm	Smallest: 2.9020 g Largest: 75.4766 g	$\rho_{Agglomerate}$ = 1510 kg/m^3
III	Agglomerates located in the upper layer of the bed	Smallest ~2 cm Largest ~ 8 cm	Smallest: 2.9020 g Largest: 75.4766 g	$\rho_{Agglomerate}$ = 1510 kg/m^3

3. Results and discussion

Smooth fluidization is essential for efficient and effective operation as it ensures good contact between the particles, hence optimal heat transfer in the bed. Smooth fluidization is a result of hydrodynamic, gravitational and inter-particle forces, and due to of the balance of forces bed agglomeration will interfere with the fluidization process. When agglomerates are present, the inter-particle forces are considerable and hence they will take control over the bed behavior.

In the present study of flow behavior in the fluidized beds, it was observed that with the presence of agglomerates, the bed was only partially fluidized. Figure 7 shows how Δp_{bed} varies with u_f for experiment (I) and experiment (II). Experiment (I) represents the flow behavior in a fluidized bed during normal fluidization, and experiment (II) represent the flow behavior in an agglomerated fluidized bed. For the agglomerated fluidized bed, Δp_{bed} was decreased and u_{mf} was increased. Decreased Δp_{bed} is a result of the bed particles growing into larger entities. These agglomerates are too large to be fluidized, and thus they will remain in the lower part of the bed and prevent the air from being evenly distributed. Moreover, bed agglomeration causes channeling and low particle-fluid contact, as the air tends to flow into the openings between the agglomerates. The poor air distribution might lead to de-fluidized volumes in the bed followed by complete de-fluidization.

The increase in u_{mf} is a result of the increased void fraction causing decreased drag forces. u_{mf} increases from 0.035 m/s in normal fluidization to 0.041 m/s in agglomerated fluidization. Lower u_{mf} means little gas bypassing and is beneficial for good mixing and high rates of heat and mass transfer. A consequence of the high u_{mf} is that the gasification process will be characterized by instabilities, with bubbling and channeling of air. Higher u_{mf} means higher air flow and thereby more oxygen mixed in the bed, which in turn may cause that the process will go towards combustion instead of gasification.

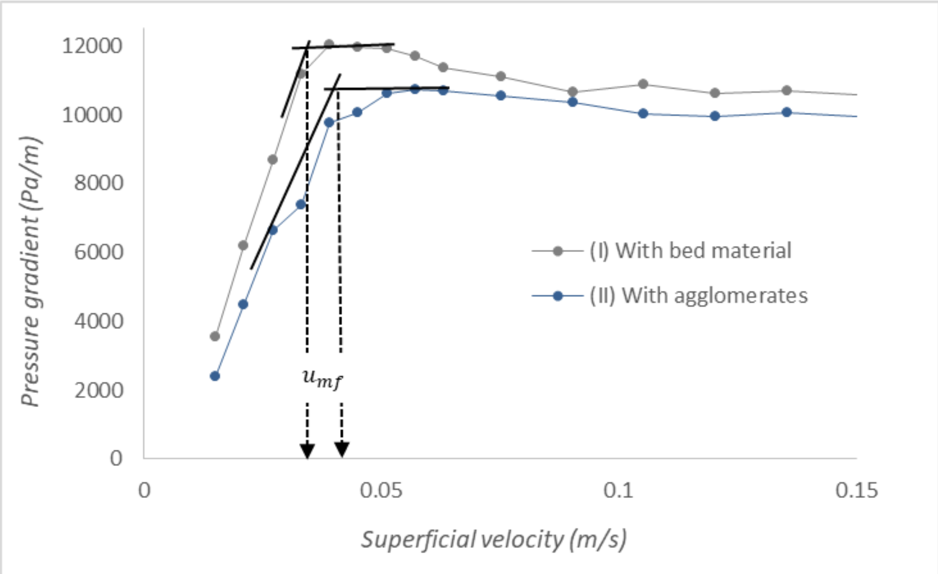

Figure 7. Fluidization in a normal and an agglomerated fluidized bed

Figure 8 shows the variation in Δp_{bed} when u_f increases for experiment (II) and experiment (III). Experiment (II) represent the flow behavior when agglomerates are placed at the bottom of the bed, and experiment (III) represent the flow behavior when the agglomerates are placed at the top of the bed. It is seen that the different location of the agglomerates lead to different fluidization processes. Agglomerates that either stick to the wall of the bed or are located in the upper layer of the bed, entail higher u_{mf} and higher Δp_{max} than agglomerates that are located at the bottom or in the lower part of the bed. u_{mf} increases from 0.041 m/s in experiment (II) to 0.057 m/s in experiment (III). The increase in u_{mf} and Δp_{max} is a result of the bed expanding causing rise in bed porosity. Increase in void fraction decreases the overall drag until it is balanced by the total weight exerted by the solid particles.

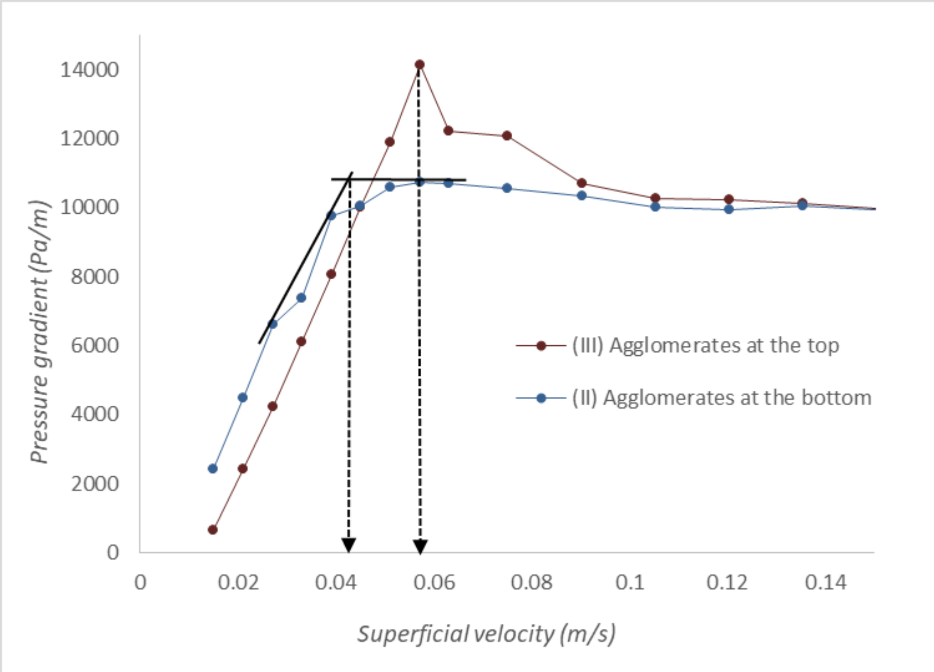

Figure 8. Fluidization in a normal and an agglomerated bed

As u_f increases beyond u_{mf}, the bubble formation increases. Figure 9 shows snapshots obtained of the bubbling behavior in the agglomerated fluidized bed during the fluidization experiments. When agglomerates were present, it was observed that the bed was not fully fluidized. In the agglomerated fluidized beds most of the bubbles collapsed at the bottom of the bed instead of passing through the entire bed (Figure 9-a). Visual observation also revealed that the bed material was in motion at the top of the bed, while the larger agglomerates remained at the bottom causing the gas to flow in channels between them (Figure 9-b). The agglomerated beds showed almost no expansion, and as the measured pressure drop was less than the bed weight indicating that the bed was not fully fluidized. In biomass gasification, this phenomenon causes improper circulation of the biomass and non-uniform temperature distribution in the bed. The non-uniform temperature distribution forms zones with de-fluidized volumes and increased temperatures. Higher temperatures increase the stickiness of the particle surfaces and might result in enhanced formation of agglomerates. Eventually, the bed takes a sluggish appearance.

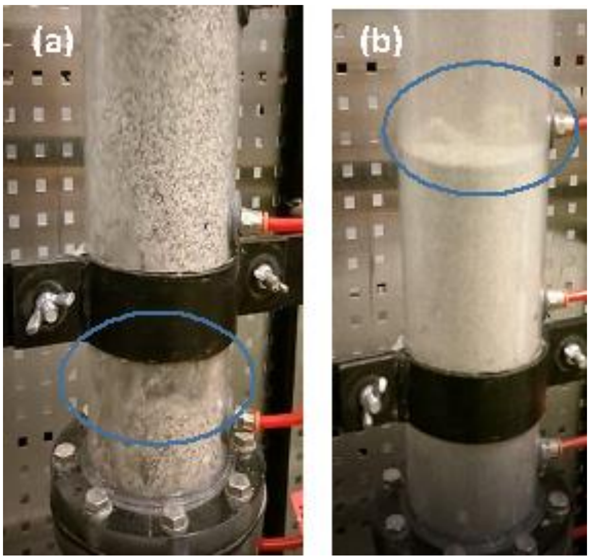

Figure 10. (a) Bubbles collapse at the bottom of the bed (b) air flows in channels of the bed.

4. Conclusion

The objective of this work was to study how agglomerates affect the flow behavior in fluidized bed gasification of biomass. The study included experiments performed in a cold flow model of a bubbling fluidized bed. The experiments were carried out with 175 μm sand particles as bed material. A mix of agglomerates of different sizes was introduced to the bed. The pressure drop across the bed and the minimum fluidization velocity were determined and the bubbling behavior was observed.

The formation of low-melting ash components such as alkali silicates creates problems in fluidized bed reactors, as the formation of sticky glassy melt causes bed particle agglomeration. This can happen when the ash particles on the bed particle surface stick together and sinter to form hard bridges between the particles. Agglomerates have peculiar shapes, sizes and densities, which make them difficult to fluidize and handle adequately. The formation of agglomerates cause instabilities with bubbling and channeling in the bed, resulting in loss of fluidization. When channeling occurs in the bed, the particle-gas contact becomes low and any heat and mass transfer operation is weakened. Consequently, de-fluidized volumes occur in the bed, which often lead to complete de-fluidization of the bed, followed by unscheduled shutdowns of the whole installation

The experiments indicate that bed agglomeration changes the flow behavior in fluidized beds. The minimum fluidization velocity increased from 0.035 m/s in the normal fluidized bed to 0.041 m/s in the agglomerated fluidized bed where the agglomerates were placed at the bottom of the bed. The minimum fluidization velocity increased further to 0.057 m/s in the agglomerated fluidized bed where the agglomerates were added from the top of the bed. During the experiments, it was observed that the pressure drop decreased and the minimum fluidization velocity increased with the presence of agglomerates in the bed. Additionally, channeling was observed in the bed, and the bubble formation and bubbles growth in the bed was interrupted.

Acknowledgement

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