EXPERIMENTAL AND COMPUTATIONAL STUDIES ON BIOMASS GASIFICATION IN FLUIDIZED BEDS

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ABSTRACT

The world's energy consumption is increasing, and research regarding utilization of renewable energy sources is crucial. Biomass for direct heating has been used for thousands of years, while in the last decades alternative ways to exploit biomass have emerged. In order to increase the efficiency and to produce more applicable products, gasification of biomass is becoming a more and more promising technology. For the gasification technology to be competitive, the understanding of the various aspects regarding the gasifier operation, which in turn influences the quality of the product gas, is of utmost importance. The main objective of this work is to investigate the effect of the air to biomass ratio on the produced gas composition in terms of the high-energy components H_2, CH_4 and CO. Experiments were performed with wood chips in a pilot scale gasification reactor. The results show that an air-to-biomass ratio less than one gives the most applicable gas composition. Biomass, like wood chips, has a peculiar shape, has a large particle size, is cohesive, and is therefore difficult to fluidize. In a fluidized bed gasifier, a bed material is used to improve the fluidization quality. Experiments were carried out in a cold bed model to study the fluidization properties of the bed material. Minimum fluidization velocities were predicted based on pressure drop in the bed.

Keywords: Baracuda, biomass, bubbling fluidized bed, CPFD, gasification, multiphase flow.

1 INTRODUCTION

The world's energy consumption is increasing, and research regarding competitive renewable energy sources is constantly crucial. The utilization of biomass for direct heating reaches back to thousands of years, while in the last decades alternative ways to exploit biomass have emerged. Burning biomass directly for producing steam, which in turn operates steam turbines, is frequently utilized. However, combustion of biomass gives limited efficiencies and field of application. In order to increase the efficiencies along with producing a more applicable product, gasification of biomass is becoming a more and more promising technology. For the gasification technology to be competitive, the understanding of the various aspects regarding the gasifier operation, which in turn influence the product quality, is of utmost importance. Different types of reactors can be used for biomass gasification, and this article focuses on bubbling fluidized bed gasifiers. Biomass, like wood chips, has a peculiar shape, has a large particle size, is cohesive, and is therefore difficult to fluidize. In a fluidized bed gasifier, a bed material (inert sand or particles with catalytic effect) is used to improve the fluidization quality. Fluidized bed gasifiers are used to achieve uniform material and heat distribution, and thereby enhancing the reaction rates and conversion efficiency of the biomass [1], [2], [3].

Gasification is a process where different types of biomass are converted into a combustible gas mixture, which has a variety of applications depending on the composition. The reaction temperature is typically 700–1100°C, and the supplied amount of oxygen should be kept relatively low to avoid combustion of the biomass. The biomass is converted into a product gas containing CO, CO_2, H_2, CH_4, H_2O and tars. Tars are heavy hydrocarbons that usually condense at temperatures around 300°C, and ideally should be broken down into lighter components [4].

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When fluidized beds are used for gasification of biomass, it is important to ensure that all the zones of the bed are kept in the fluidized regime during the entire operation time. It is therefore crucial to study the fluidization properties of the bed material. The aim of this work is to collect and analyze data from the operation of a gasifier. Special attention is put towards air flow to biomass ratio and the quality of mixing in the gasifier.

2 MATERIAL AND METHOD

Experiments are performed both in a cold fluidized bed and in a fluidized biomass gasifier.

2.1 Cold fluidized bed

Experiments are performed in a cold bed to study the fluidization properties. It is important to know at which velocity different types of bed materials start to fluidize, and the range of velocities that will keep the bed in the bubbling fluidized regime. Therefore, a cold bed can be used to study the fluidization behavior of the bed material used in a gasification reactor. The results can further be scaled to satisfy the conditions in the gasifier, or the gasifier conditions can be scaled to give the actual cold bed conditions. The results from the cold bed can also be used to verify a computational particle fluid dynamics (CPFD) model, which can be further used to simulate the flow behavior in the biomass gasifier.

The cold bed setup is presented in Fig. 1. The setup consists of transparent cylinder with a height of 1.63 m and a diameter of 0.084 m. Pressure sensors are installed along the height of the cylinder, and the distance between the sensors is 0.1 m. The cylinder is open to atmosphere at top. Desired amount of bed material is poured down from top to form an initially fixed bed. The air distributor is a porous plate and the location is indicated in the figure. The pressure sensor, P2, is located 0.035 m above the gas distributor. The pressure sensors are connected to a LabVIEW program, where the pressure data are logged and stored. The program also controls and registers the air flow rates.

Sand particles with mean diameter of 296 μm and 636 μm were used in the experiments. The mean diameter is determined from sieving analysis, and is based on mass. The density of

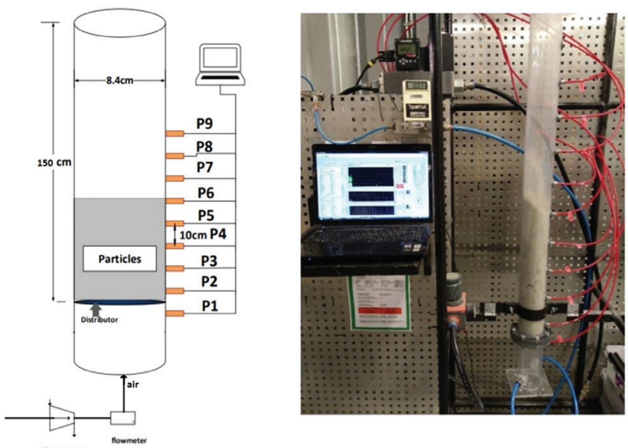

Figure 1: Experimental setup for the cold fluidized bed.

Table 1: Properties of sand particles and air.

Particle density	2,650 kg/m^3
Particle sphericity (round sand)	0.85
Mean particle size (smaller particles)	296 μm
Range of particle sizes (smaller particles)	200–425 μm
Mean particle size (larger particles)	636 μm
Range of particle sizes (larger particles)	425–800 μm
Bulk density (smaller particles)	1,398 kg/m^3
Bulk density (larger particles)	1,388 kg/m^3
Air density	1.225 kg/m^3
Air viscosity	$1.78 \cdot 10^{-5}$ Pa s
Bed height	0.21 m

the sand particles is 2,650 kg/m^3. Air at ambient pressure and temperature was used as the fluidizing gas. The bed height was 0.21 m, which corresponds to an aspect ratio (bed height/diameter) of 2.5. The gas flow rate was varied stepwise to determine the transition from fixed to fluidized and bubbling bed. The bulk density was measured to be 1,398 kg/m^3 for the smaller particles and 1,388 kg/m^3 for the larger particles. The properties of air and sand are summarized in Table 1.

2.2 Gasifier

Experiments were also carried out in a pilot fluidized bed gasifier. The purpose of the experiments was to study the operation of a biomass gasifier and how the composition of the product gas was affected by different operational parameters. Special considerations for these experiments were put towards the air flow to biomass ratio. The experiments also aim to investigate whether proper mixing of biomass, bed material and air takes place in the reactor during the gasification process. The degree of mixing is evaluated based on the temperature in the reactor.

The experimental setup consists of a cylindrical column with a height of 1.0 m and an internal diameter of 0.10 m. To minimize heat loss, the inner wall of the bed reactor is coated with a refractory material. Electrical heaters are installed at the reactor wall to supply the heat needed during operation. The biomass, in this case wood chips, was fed to the reactor via screw conveyors. The conveyors were calibrated for the actual type of biomass before the tests. The flow rate of biomass is controlled from a programmable logic controller. Air was preheated and fed to the gasifier at a desired flow rate. The gasifier was preheated up to 300°C to avoid cold spots [5]. Samples of the product gas were taken regularly at intervals of 10 min. A gas chromatograph was used to analyze the samples with respect to the gas composition. Figure 2 shows a schematic illustration of the biomass gasification reactor. Specification of the gasification reactor and the operating conditions are summarized in Table 2.

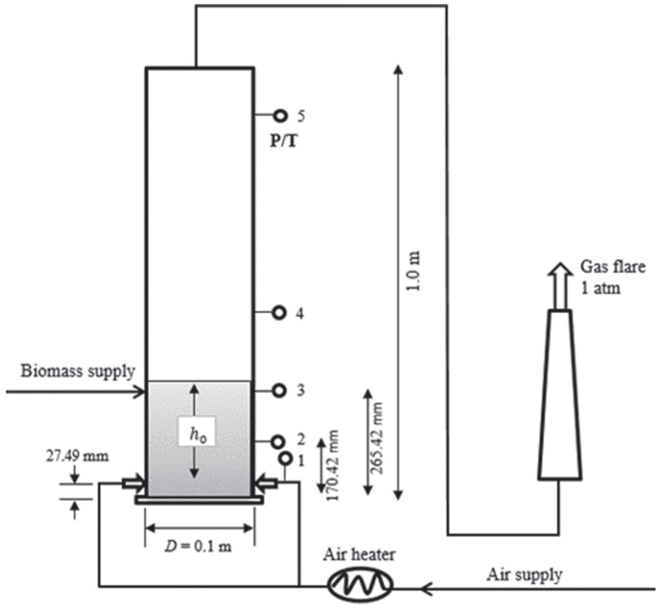

Figure 2: A schematic illustration of the biomass gasification reactor. P/T indicate pressure and temperature sensor probes and h_0 is the initial bed height above the air introduction points [6].

Table 2: Operational properties.

Operational properties	
Bed height	26.5 cm
Biomass feeding	2 cm below top of the bed
Air feeding	2 cm above bottom of the bed
Bed material: Sand	
Density (sand)	2,650 kg/m^3
Range of particle sizes (sand)	400–750 µm
Mean particle size (sand)	610 µm
Biomass: Wood chips	
Density	411 kg/m^3
Length	5–12 mm
Width	5–12 mm
Thickness	1–5 mm
Shape	Rectangular
Mean diameter	d_p = 6.87 mm
Shape factor	0.75

Fluidizing agent: Air	
Air density (800°C)	kg/m^3
Air viscosity (800°C)	Pa s
Air density (900°C)	kg/m^3
Air viscosity (900°C)	Pa s

3 RESULTS

This chapter presents results obtained from experiments in a cold fluidized bed and in a biomass gasifier. In addition, results from modelling and simulation of the cold bed and the gasifier are also presented.

3.1 Cold bed experiments

The experiments were performed with sand with a mean diameter of 296 μm and 636 μm to determine the minimum fluidization velocities and the range of velocities that can be used to keep the fluidization in the bubbling regime. The results are shown in Figs. 3 and 4 for the small and large particles, respectively. The results are presented as pressure drop per meter height of the particle bed versus superficial velocity. The minimum fluidization velocity is determined as the velocity when the pressure drop is at the maximum value. The minimum fluidization velocity is 0.09 m/s for the small particles and 0.33 m/s for the larger particles, which means that the minimum fluidization velocity increases significantly with increase in particle size. This is important to take into consideration when choosing bed material for the biomass gassifier. The bed containing small particles can be run in the bubbling regime at least up to a superficial velocity of 0.18 m/s. The tests with the larger particles were run with velocities up to 0.62 m/s, and the plot indicates that the bed will stay in the bubbling regime in the range of velocities from 0.33 m/s to 0.62 m/s.

3.2 CPFD modelling and simulation

The results from the cold bed experiments were further used to validate a CPFD model using the commercial software Barracuda VR 17.1.0. In Barracuda, the Eulerian approach is used

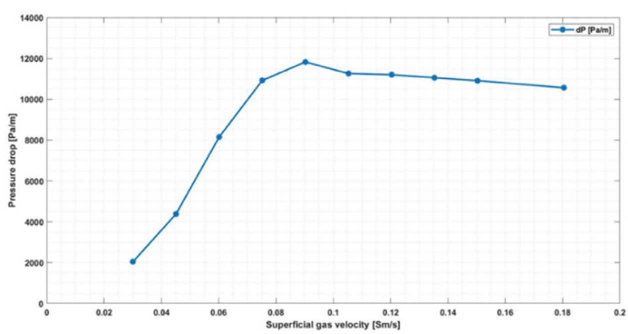

Figure 3: Pressure drop and minimum fluidization velocity from fluidization experiments using 296 μm sand, with aspect ratio of 2.5.

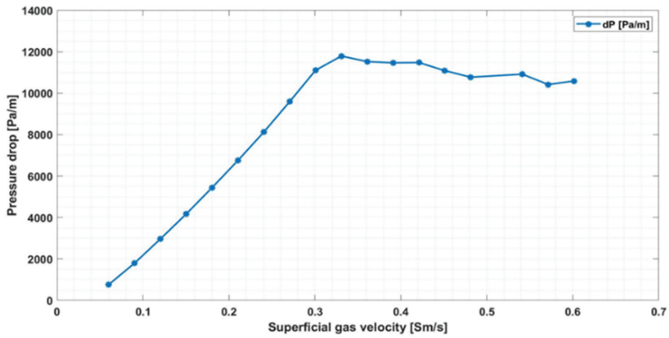

Figure 4: Pressure drop and minimum fluidization velocity from fluidization experiments using 636 µm sand, with an aspect ratio of 2.5.

for solving the fluid phase and the Lagrangian approach for the modelling of the particle phase [7]. The Wen and Yu drag model is used in the simulations [8]. The sphericity was set to 0.84 and the close pack volume fraction was set to 0.54. Detailed information about transport equations, solvers and model development in Barracuda is presented in [9], [10], [11]. The validation of the model is performed with particles with a mean diameter of 293 µm. The computational and experimental plots are compared in Fig. 5. The simulations agree very well with the experimental data regarding the minimum fluidization velocity and the pressure drop in the bubbling regime. Deviations are observed in pressure drop through the fixed bed, which may be due to variations in particle size distribution in the simulation compared to the experimental study. The deviation can also be due to the value of the maximum packing used in the simulated fixed bed. However, the model will be used to predict flow behavior in the bubbling

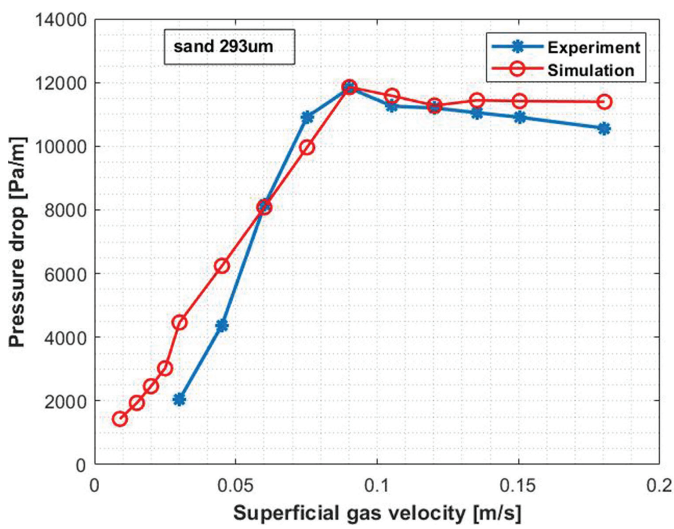

Figure 5: Comparison of experimental and simulated results; sand particles with a mean particle size of 293 µm.

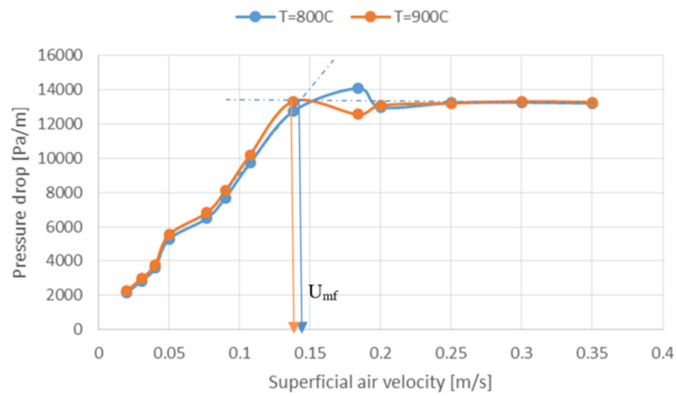

Figure 6: Pressure drop and minimum fluidization velocities from simulations using 610 μm sand particles, aspect ratio of 2.5 and temperatures 800°C and 900°C.

fluidized bed gasifier, and it is most crucial that the model is capable of predicting the bubble regime well.

The gasifier operates at temperatures between 800˚C and 900˚C. If small particles are used in the gasifier, entrainment of bed material may occur at the required gas flow rates. It was therefore decided to run the gasifier with sand particles with mean diameter of 610 μm as the bed material. Simulations based on the validated model were performed to find an acceptable range of gas velocities that could be used to keep the bed in the bubbling regime. The results are presented in Fig. 6. The minimum fluidization velocity is 0.144 m/s at 800˚C and 0.138 m/s at 900°C. This indicates that it is necessary to run the gasifier at velocities well above 0.144 m/s to ensure that the bed is fluidized.

3.3 Gasification of biomass

Three different air-to-biomass ratios were used to study the effect on the composition of the product gas. The biomass flow rate was kept constant at 2.03 kg/h, whereas the air flow rates were 1.70 kg/h, 2.30 kg/h and 3.00 kg/h. The corresponding air to biomass ratios were 0.84, 1.13 and 1.48. The superficial velocities at 800°C and 900°C are presented in Table 3.

The total chemical reaction that occurs during the gasification process is an endothermic reaction, which implies that the process need heat supply. It is important to keep the oxygen supply low to obtain gasification and produce a high energy gas containing mainly CO, H_2 and some CH_4. If the air flow rate is too high, combustion or partly combustion will occur, and the product gas will contain more CO_2 and H_2O and less of the gas components with high calorific value.

If cellulose ($C_6H_{10}O_5$) is assumed to be the organic molecule in wood-chips, the stoichiometric air to biomass ratio can be calculated from:

$$C_6H_{10}O_5 + \left(6 + \frac{10}{4} - \frac{5}{2}\right)\left(O_2 + 3.76N_2\right) \rightarrow 6CO_2 + 5H_2O + \left(3.76 \cdot 6\right)N_2 \tag{1}$$

According to the balanced equation, the stoichiometric air to biomass ratio (mass of biomass/mass of air) is 5.08. The equivalence ratio, ϕ, is the actual air to biomass ratio divided by the stoichiometric air to biomass ratio:

$$\phi = \frac{\left(\text{Air}/\text{Biomass}\right)_{\text{actual}}}{\left(\text{Air}/\text{Biomass}\right)_{\text{stoich}}} \tag{2}$$

The equivalence ratios for the gasification experiments are given in Table 3, and are low in all the experiments. Figure 7 shows the composition of the product gas for the three different air-to-biomass ratios. When the air-to-biomass ratio is low, the equivalence ratio is also low, and gasification is promoted. At air-to-biomass ratio of 0.84, the superficial gas velocity is about 20% above the minimum fluidization velocity at 800°C, and this velocity was considered as the lowest velocity that could be used to ensure fluidization. The results show that the content of H_2 and CO and CH_4 in the product gas decreases with increasing equivalence ratio, which is in agreement with the theory. However, the superficial gas velocity, and thereby the equivalence ratio has to be kept high enough to avoid defluidization. The temperature in the gasifier may vary with time, and it has to be taken into consideration that the minimum fluidization velocity increases with decreasing temperature.

The biomass gasification reactor is operated in the bubbling fluidized bed regime to achieve proper mixing in the gasifier. The degree of mixing in the gasifier influences on the quality of the product gas and proper mixing entails that the biomass is not accumulated in a part of the gasifier, but is evenly distributed in the reactor together with the bed material and the gas. Figure 8 shows the time averaged temperatures for different zones in the reactor, for the three different air-to-biomass ratios used in the experiments. The positions of the temperature sensors are shown in Fig. 2.

A good indication of the degree of mixing is the deviation in temperature over the gasifier. If a good mixing is achieved, the temperature will be rather constant over the entire bed. The highest air-to-biomass ratio (1.48) gives the lowest temperature deviation and hence the best mixing. The air-to-biomass ratio of 1.13 gives a constant value over the bed, but the temperature increases a little in the freeboard. The lowest air-to-biomass ratio (0.84) gives the largest temperature deviation in the reactor, which indicates that the mixing is not good enough.

Table 3: Gasification parameters.

Air to biomass ratio (kg air/kg biomass)	0.84	1.13	1.48
Mass flow rate of air (kg/s)	1.7	2.3	3.0
Mass flow rate of biomass (kg/s)	2.03	2.03	2.03
Superficial gas velocity (m/s), T = 800°C	0.170	0.230	0.300
Superficial gas velocity (m/s), T = 900°C	0.186	0.252	0.328
Minimum fluidization velocity sand (m/s), T = 800°C	0.144	0.144	0.144
Minimum fluidization velocity sand (m/s), T = 900°C	0.138	0.138	0.138
Equivalence ratio	0.17	0.22	0.29

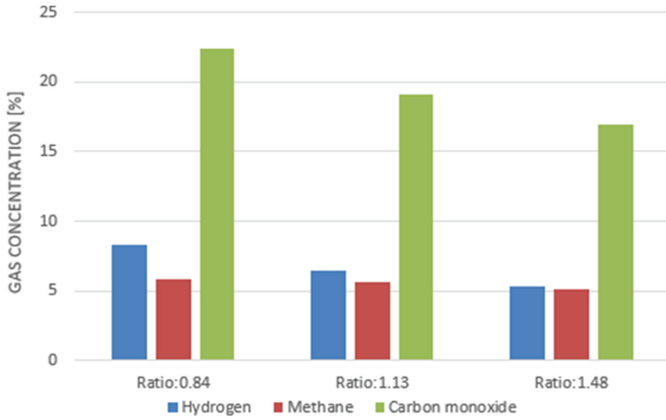

Figure 7: Comparison of product gas composition for different air to biomass ratios.

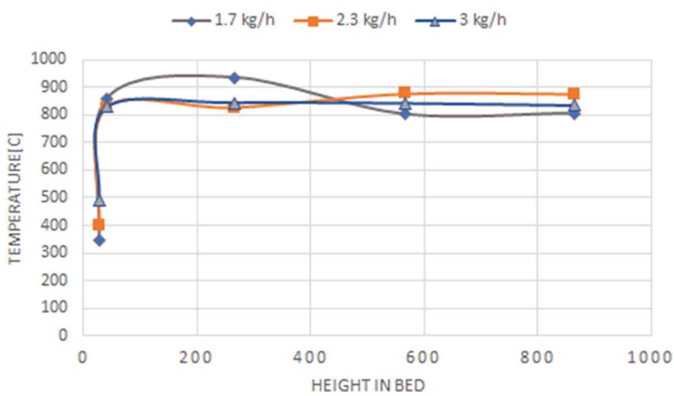

Figure 8: Average temperature over bed height for varied air flow rate.

However, the lowest air-to-biomass ratio yields the product gas with the highest calorific value. More experiments are needed to study the degree of mixing in the gasifier.

4 CONCLUSION

The main objective of this work was to investigate the effect of the air to biomass ratio on the produced gas composition in terms of the high-energy components H_2, CH_4 and CO. Biomass, like wood chips, has a peculiar shape, has a large particle size, is cohesive, and is therefore difficult to fluidize. In a fluidized bed gasifier, a bed material is used to improve the fluidization quality. Experiments were carried out in a cold bed model to study the fluidization properties of the bed material. Minimum fluidization velocities were predicted based on pressure drop in the bed. The experimental results were used to validate a CPFD model using Barracuda. The validated model was used to predict the minimum fluidization velociy and the transition to the bubbling regime in a gasifier run at temperatures 800°C and 900°C. The data were used for gasification tests to ensure that the gasifier was operated in the bubbling fluidization regime. The experiments were performed with wood chips in a pilot scale gasification reactor. The results show that a rather low air-to-biomass ratio of 0.84 gives the most applicable gas composition. More experiments are needed to study the degree of mixing at low air to biomass ratios.

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