Investigation of flow behaviour in biomass gasifier using Electrical Capacitance Tomography (ECT) and pressure sensors

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Abstract:

The particles in a biomass gasifier are mainly a mixture of wood chips, char particles and bed material. The char-wood particles have a significant lower density than the bed material, and also a wider range of particle sizes and larger mean particle diameter. The difference in particle properties may cause segregation and thereby influence on the fluidization properties and the flow behavior in the bed. The aim of this work is to study the fluidization properties in cold fluidized bed with different mixtures of particles. ZrO and plastic particles with a density ratio of 6, are used in the experiments to simulate the bed material and the char-wood particles in a biomass gasifier. Experiments are performed in cylindrical beds with uniform air distribution. The fluidization properties are studied using pressure sensors and Electrical Capacitance Tomography (ECT). The ECT system is a non-intrusive measurement system and is a suitable method for monitoring the internal flow behavior of fluidized bed. The experimental results show that the minimum fluidization velocities very much depend on the particle composition in the bed. The fluidization velocity reaches a maximum when 20% plastic particles are added to the ZrO powder and decreases again when the fraction of plastic beads are further increased. The theoretical minimum fluidization velocities for the different mixtures agree well with the experimental data. The standard deviations of the pressure and the ECT measurements showed that the fluidization velocities are higher in the lower part than in the higher part of the bed. This observation is more significant in the mixtures with high fraction of plastic particles. This indicates that the plastic particles moves upward in the bed and that mainly ZrO particles are present in the lower part of the bed. This is also visually observed during the experiments. Segregation can give low degree of particle motion in parts of the bed. Investigation of fluidization behavior of the different mixtures in this study may be useful as an initial step of analyzing the complex system of a bubbling fluidized bed gasifier.

1. Introduction

Production of heat and power based on biomass from forestry has during the last decade become a very important technology. Gasification of biomass is a part of the process, and researchers have studied different types of fluidized bed reactors to find an optimal design. The efficiency of a fluidized bed reactor is highly dependent on the powder properties and the flow conditions which also control the mixing of the bed. Particle density, particle sizes, range of particle sizes and superficial gas velocity are influencing on the flow behavior, mixing and segregation. The particles in a biomass gasification reactor are a mixture of wood chips, char particles and bed material. The feed to the gasifier consists of wood chips with a size of 1-5 cm and a large variety of shapes. During the gasification the size of the wood chips decreases significantly from large wood chips fed to the reactor to unreacted char particles with a wide range of particle sizes. The wood chips and the char particles have a significant lower density than the bed material. The density difference may cause segregation and thereby influence on the fluidization properties and bubble activities. In addition the wood chips, the char and the bed material have a wide range of particle sizes. When the range of particles sizes is wide, the particles will have a tendency to segregate. Good mixing in the gasifier is important to secure significant heat transfer in the bed.

2. Concept and methodology

The aim of this work is to study the fluidization properties in a gasification reactor and to investigate how mixtures of different particle sizes and density influence on the fluidization properties. In a gasifier a typical temperature of the inlet steam is 400°C and the density is about 0.32 kg/m^3. The density of the bed material and the char/wood particles are about 2500 and 400-500 kg/m^3 respectively. In this study air with density 1.18 kg/m^3 is used as the fluidization gas. The density ratio air/steam is about 4, and the particle ratio should be about the same to be able to simulate the actual gasification reactor. ZrO with density 5850 kg/m^3 and plastic beads with density 964 kg/m^3 are used to simulate the bed material and the char/wood particles respectively. The density ratio of the particles used in the experiments is about the same as the density ratio of the bed material and the char/wood particles in a gasification reactor. The experiments are performed in fluidized beds with diameter 0.084 and 0.104 m. The experimental set up is presented in Fig. 1. Pressure sensors are used to measure flow behavior in the 0.084m bed, whereas Electrical Capacitance Tomography (ECT) is the measurement system used in the 0.104 m bed. Fig. 2 shows a sketch of the bed with pressure sensors. The sensors used in this study are named p2, p4, p5 and p6 and are located 0.03, 0.23, 0.33 and 0.43 m above the air distributor.

The ECT system is used to investigate the fluidization properties and the bubble activity in the bed. The ECT system is a non-intrusive measurement system and is a suitable method for monitoring the internal flow behavior of fluidized beds. The sensors are placed on the outside of the non-conductive experimental bed and the sensors are measuring flow behavior in two planes. The fluidization properties have been studied by using ECT in combination with a reconstruction program developed at Telemark University College [1]. The reconstruction program creates images of the fluidized bed reactor and the flow properties like minimum fluidization velocity and bubble activity can be studied. A sketch of the ECT system is presented in Fig. 3. The figure also shows a cross sectional view of the ECT sensor together with a cross sectional image. The sensors are located at height 0.156 m (plane1) and 0.286 m (plane2) above the air distributor. The ECT-system is described in detail in [1].

Fig. 1: Experimental set-up. Fluidized bed with pressure reduction valve, digital flow controller, pressure sensors.

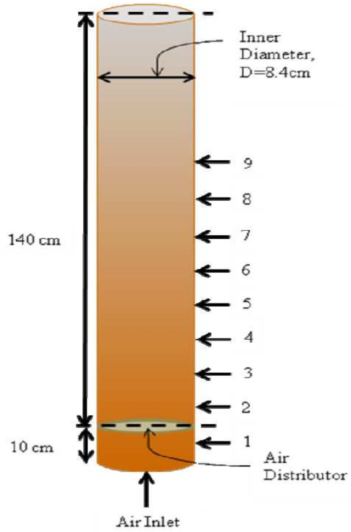

Fig. 2: Sketch of 0.084 m bed with pressure sensors.

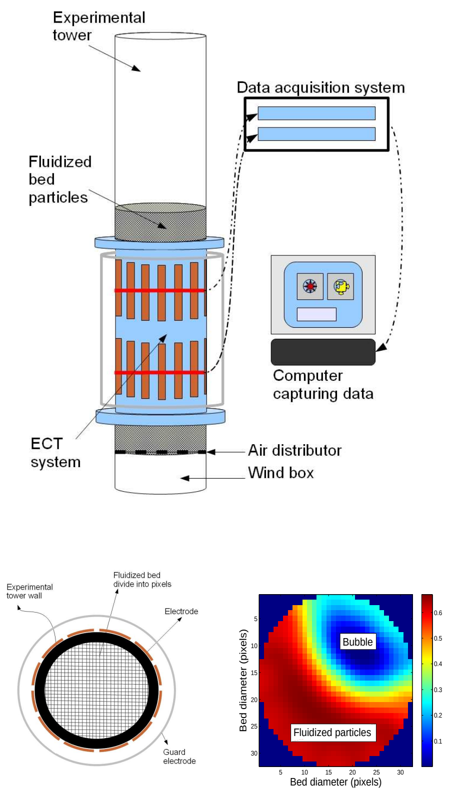

Fig. 3: Sketch of the 0.104 m bed with ECT system.

3. Results and discussion

Inside the gasifier there is simultaneous existence of unreacted wood chips, reacting wood chips, char particles and bed material having a large range of particle sizes, shape and density. Consequently the particle composition is varying along the bed height which makes it difficult to predict the fluidization behavior of the gasifier in an accurate way using a cold bed. To study the mixing and segregation tendency in a fluidized bed gasifier, ZrO and plastic beads with density ratio 6 are used. In a gasifier the particle size distribution is wide, from large wood chips (1-5 cm), all sizes of char particles and the bed material with particle size about 400-600 μm. The plastic beads with large particle sizes and wide shape distribution resemble the average particle size and shape of the char inside gasifier. ZrO has about the same particle size distribution as the bed material in a gasifier. Investigation of fluidization behavior of mixtures of the two types of particles with different particle size and shape as well as density can only be an initial step of an analysis of the complex system of a bubbling fluidized bed gasifier. Air is used as fluidization gas in the experiments whereas steam at $400^{\circ}C$ is used in a real gasifier. The air/steam ratio is about 4, and to get the correct picture of the fluidization conditions in the gasifier based on experiments in cold bed, the particles used in the experiments should have a density 4 times the particles in the hot reactor. Particles with this high density were not available, and lighter particles are therefore used. However the density ratio bed material/char-wood particles are maintained. The experiments are performed with pure ZrO and plastic particles, and with different mixtures of these two types of particles. The experimental test matrix is presented in Tab. 1.

The pressure drop as a function of superficial velocity for pure ZrO and plastic beads are shown in Fig. 4 and 5 respectively. The analysis of the experimental results shows that the minimum fluidization velocities (U_{mf}) for ZrO and plastic beads are 0.67 m/s and 0.85 m/s respectively. The higher U_{mf} for the plastic beads is due to the large particle size and high void fraction.

Particle	Mean particle size [µm]	Initial bulk density [kg/m^3]	Initial void fraction
ZrO	709	3857	0.34
ZrO+10% plastic	709 /3500	3680	0.31
ZrO+20% plastic	709 /3500	3488	0.28
ZrO+30% plastic	709 /3500	3355	0.25
ZrO+40% plastic	709 /3500	3237	0.23
Plastic beads	3500	564	0.42

Tab. 1: Test matrix

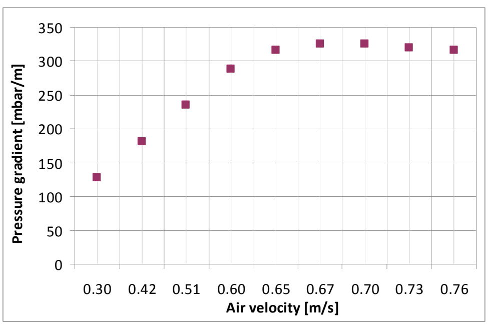

Fig. 4: Pressure gradient as a function of superficial air velocity. ZrO

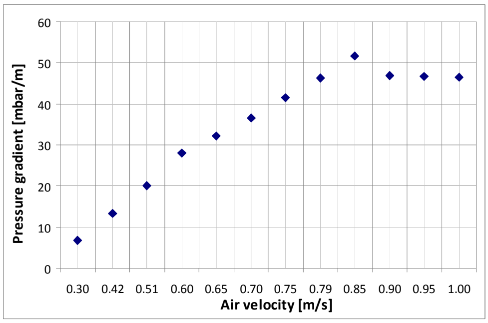

Fig. 5: Pressure gradient as a function of superficial air velocity. Plastic particles.

Fig. 6 show the pressure drop as a function of superficial velocity for ZrO and four different mixtures of ZrO and plastic. The pressure drop is the average pressure drop in the bed. When mixing plastic and ZrO particles the initial void fraction changes. The minimum fluidization velocity and the pressure drop (dp/dx) are strongly dependent on the void fraction in the bed. U_{mf} for pure ZrO is about 0.67 m/s. As can be seen from Fig. 6, U_{mf} increases to about 0.75 m/s when 10 vol% plastic particles are mixed with the ZrO, and increases further to 0.77 m/s when the vol% of plastic beads is increased to 20%. When the vol% of plastic beads are increased to 30%, U_{mf} decreases to 0.70 m/s and the mixture with 40 vol% plastic gives U_{mf} 0.65m/s which is lower than U_{mf} for the pure ZrO. The pressure drop (dp/dx) in the bed is about 350 mbar/m for the mixtures with 10, 20 and 30 vol% plastic beads, whereas dp/dx is about 330 mbar/m for pure ZrO and the mixture with 40% plastic beads.

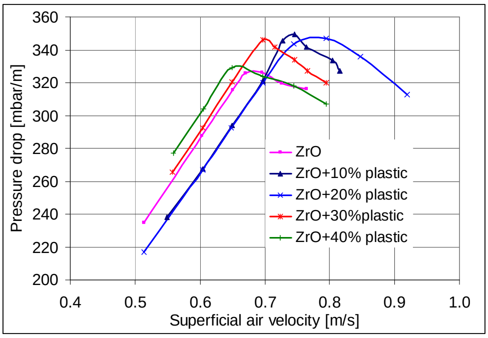

Fig. 6: Pressure gradient as a function of superficial air velocity. ZrO and different mixtures of ZrO and plastic.

The minimum fluidization velocity is a function of particle size, particle shape, particle density and void fraction. The minimum fluidization velocity can be developed from the buoyant-equals-drag balance. Using Ergun equation, the theoretical minimum fluidization velocity is given by [2,3]:

$$U_{mf} = \frac{(\Phi \cdot d_p)^2 \Delta\rho \cdot g}{\mu} \cdot \frac{\varepsilon_{mf}^{\ 3}}{1-\varepsilon_{mf}} \qquad (1)$$

where Φ is the shape factor, ε is the void fraction, d_p is the particle diameter, $\Delta\rho$ is the particle-gas density difference and μ is the gas viscosity. Ergun equation is used to investigate the effect of the different parameters on the fluidization properties. The theoretical minimum fluidization velocities are calculated for the pure plastic and ZrO powders and for the different mixtures of the two types of powders. The initial void fractions in Tab. 1 are used in the calculations of the mixtures.

The comparison is shown in Fig. 7. The calculations are based on the average particle density and average particle size and shape. The pure ZrO and plastic particles show decreasing theoretical U_{mf} with increasing solid volume fraction. The deviation between the two curves decreases with increasing solid volume fraction. The calculated U_{mf} for mixtures (ZrO with 0, 10, 20, 30, 40 vol% plastic beads) shows the same tendency as the experiments by having a maximum U_{mf} for mixture with 10 – 20 % plastic particles. The experimental U_{mf} is higher than the theoretical. The deviation between experimental and theoretical results increases from 6% to 17% with increasing vol% of plastic beads. The non-linear behavior of the U_{mf} as a function of solid volume fraction may be due to the significance of the different particle properties in the mixtures. Higher fraction of plastic particles gives decreasing void fraction, particle density and average shape factor in the mixture. These three parameters contribute to decrease the U_{mf} when the fraction of plastic particles is increased. The mean particle diameter increases with increasing fraction of plastic particles and contribute to increase the fluidization velocity. When the increase in d_p is more dominant than the decrease of ε, $\Delta\rho$ and Φ, the U_{mf} increases. The U_{mf} decreases again when the changes in ε, $\Delta\rho$ and Φ become more significant.

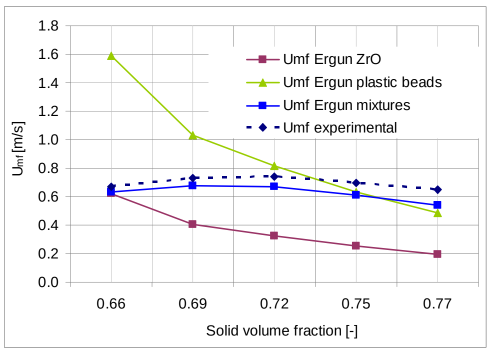

Fig. 7: Comparison of experimental and calculated minimum fluidization velocity as a function of solid volume fraction.

In addition to investigate the changes in minimum fluidization velocity with the changes in vol% of large particles with low density, the aim of this study is also to investigate the segregation tendencies for the different mixtures. The pure ZrO and plastic powders have both a rather narrow particle size distribution, and segregation is not expected to occur in those experiments. The segregation tendency is checked by plotting the pressure standard deviation at different heights of the bed. The standard deviation is zero until the bed starts to fluidize, and for the pure powders it was found that the fluidization occurred at the same velocity at all levels in the bed. To investigate the fluidization velocity and the segregation tendencies of the different mixtures of particles, the pressure standard deviation at the bottom and the top of the bed is plotted. Fig. 8 and 9 show the results from the experiments with 10 and 20 vol% plastic particles. No significant deviation of fluidization velocity at different levels of the bed can be observed from the pressure standard deviation for these two cases. However picture from experiments with 10 vol% plastic, presented in Fig. 10, shows that the plastic particles move to the top of the bed when the velocity is increased above the minimum fluidization velocity. This segregation tendency was also observed at velocities below minimum fluidization.

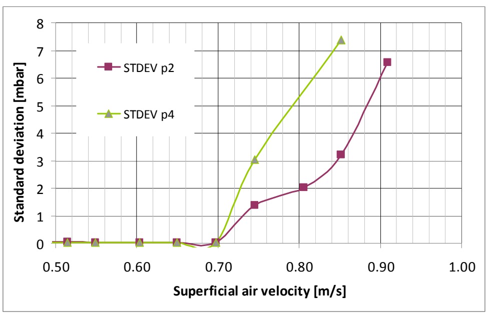

Fig. 8: Pressure standard deviation as a function of superficial velocity at two heights. ZrO with 10% plastic.

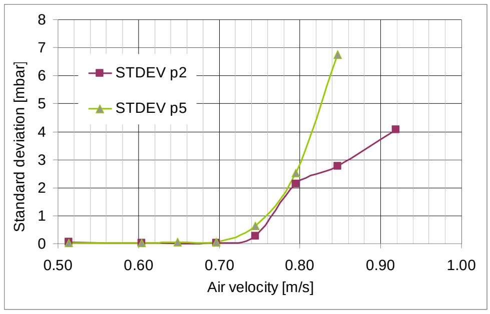

Fig. 9: Pressure standard deviation as a function of superficial velocity at two heights. ZrO with 20% plastic.

In the case of air velocity much higher than minimum fluidization, the mixing occurs mainly in the upper part of the bed.

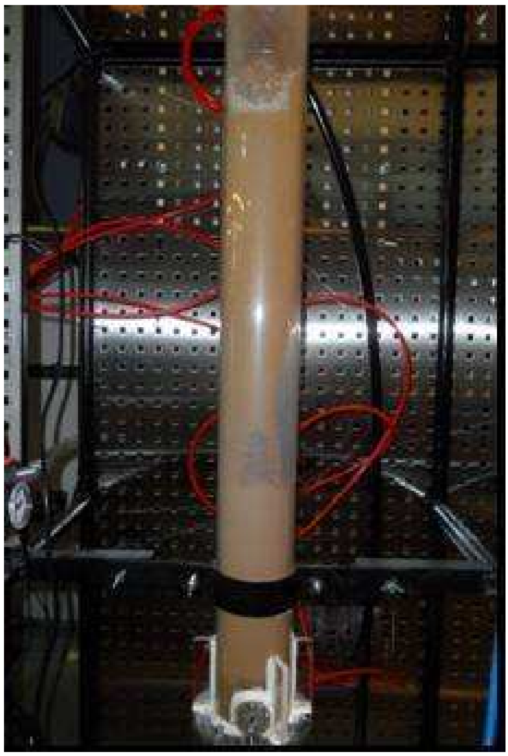

Fig. 10: Segregation. ZrO+10% plastic beads

Fig. 11 and 12 show the pressure standard deviation for the 30 and 40 vol% mixtures respectively. For these cases the minimum fluidization velocity decreases from the bottom to the top of the bed.

According to the pressure standard deviation for the 30% mixture, the upper part of the bed starts to fluidize at superficial velocity 0.65 m/s, whereas the bottom part starts to fluidize at 0.70 m/s. This indicates that the concentration of plastic particles is highest in the upper part of the bed. The mixture with 40% plastic beads shows the same tendency. The fluidization velocities are 0.61 m/s in the upper part and 0.65 m/s in the lower part of the bed. The U_{mf} in the bottom part is close to U_{mf} for pure ZrO. This indicates that the concentration of ZrO is high in the lower part of the bed and that the plastic particles tend to move upwards and are well mixed with ZrO in the upper part of the bed.

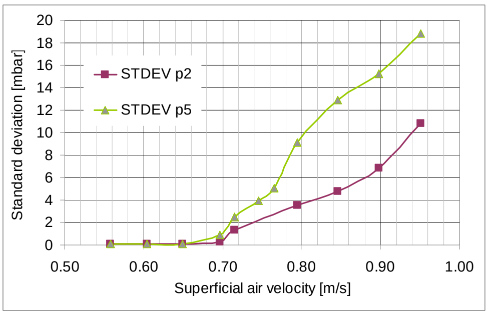

Fig. 11: Pressure standard deviation as a function of superficial velocity at two heights. ZrO with 30% plastic.

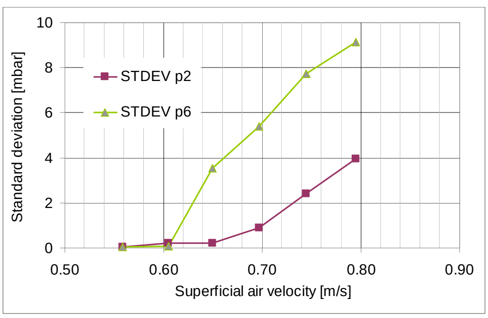

Fig. 12: Pressure standard deviation as a function of superficial velocity at two heights. ZrO with 40% plastic.

The experimental results from all the mixtures show a significant deviation between the pressure standard deviation in the upper and lower part of the bed at velocities above U_{mf}. This indicates that the bubble activity increases with height in the bed.

Experiments with 10 and 20 vol% plastic beads were also performed using ECT (Electric Capacitance Tomography). The ECT system produces signals that are converted to solid volume fraction at two levels in the bed. The measuring planes are located 0.156 m and 0.286 m above the air distributor. The solid volume fraction standard deviations for the two cases are presented in Fig. 13. For the 10% mixture ECT gives slightly higher U_{mf} in the lower part than in the upper part of the bed. The velocities are about 0.75 and 0.74 m/s. According to the ECT results for the 20% mixture, the U_{mf} increases from 0.80 m/s at the upper plane to 0.85 m/s in the lower plane. These results deviate from the results measured with pressure sensors. The deviations may be due to variations in segregation in the different experimental series. The different bed diameter of the ECT (0.104 m) and the pressure measurement (0.084 m) systems may also influence somewhat on the results. The fluidization properties in the smallest bed may be influenced by the wall effects. The tendency for all the mixtures is that segregation will occur when larger particles with low density are mixed with smaller particles with high density. Segregation may cause low degree of particle motion in the lower part of the bed.

Fig. 14, 15 and 16 show the bubble activity as a function of time at superficial velocity 0.8, 0.9 and 1 m/s respectively. The figures show the bubble activity for the 10% mixture at the two ECT planes. In Fig. 14 the superficial velocity is slightly above the U_{mf}, and it can be seen that at plane1 no bubbles have appeared whereas at plane2 a few small bubbles are observed. Fig. 15 and 16 show that the bubble frequency and bubble sizes increase significantly with gas velocity. It is also obvious that the bubble activity changes significantly from plane1 to plane2. This tendency can be observed for all the velocities. The analysis of the pressure measurements showed a similar variation in bubble activity from the lower to the upper part of the bed.

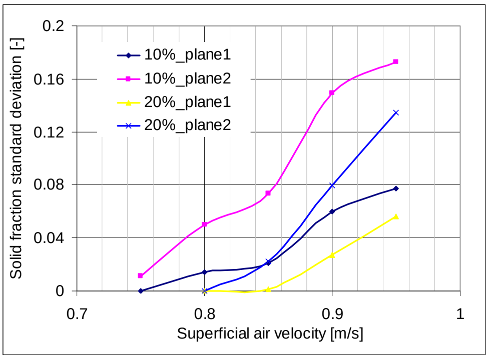

Fig. 13: Comparison of minimum fluidization velocities for different mixtures

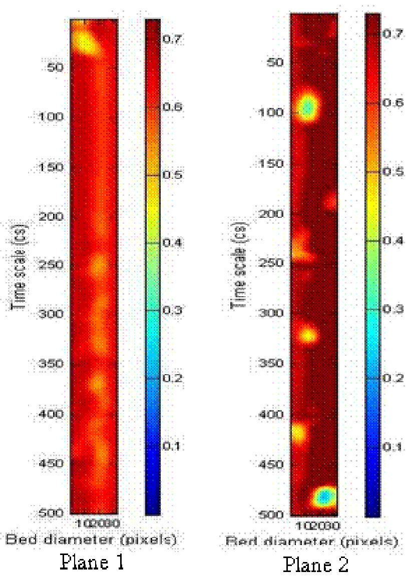

Fig. 14: Bubble distribution. Air velocity 0.8 m/s. ZrO+10% plastic beads

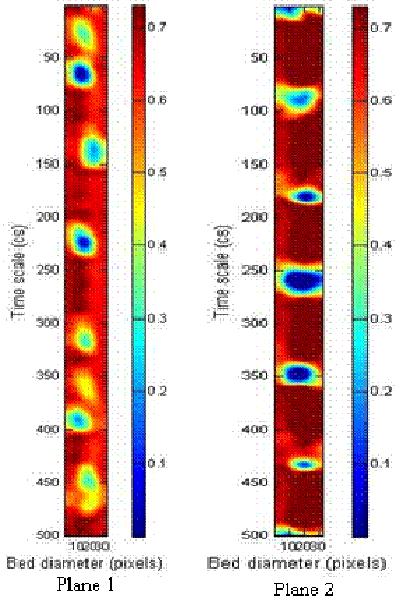

Fig. 15: Bubble distribution. Air velocity 0.9 m/s. ZrO+10% plastic beads

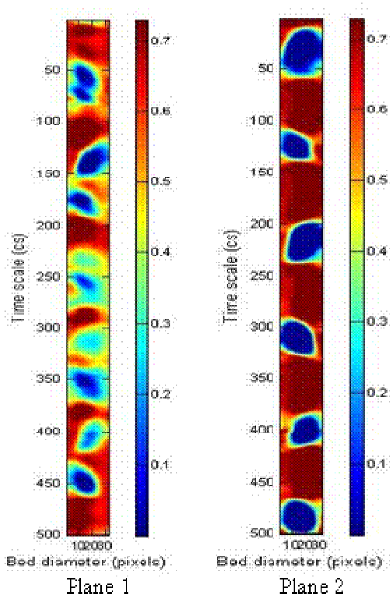

Fig. 16: Bubble distribution. Air velocity 1 m/s. ZrO+10% plastic beads

The experimental results obtained for ZrO and plastic beads can be used to predict the tendencies of flow behavior in a gasification process. In a bubbling fluidized bed gasifier, the bed material is mixed continuously with char and wood particles of lower density and significantly higher mean particle size. The experimental data indicates that the mixing of char/wood with bed material depends on the fraction of char/wood particles. Char particle and wood chips have not only large range of particle size distribution but also large range of shape distribution. Experimental results show that the minimum fluidization velocity strongly depends on the sphericity of the particles as well. In order to make char and bed material well mixed inside the gasifier, the ratio of char particles to bed material should be rather high. Consequently this will give lower circulation of bed material. Good mixing promotes higher degree of heat transfer. The steam flow rate in a gasifier depends on the minimum fluidization velocity. Lower minimum fluidization velocity reduces the required steam flow rate. This secures less consumption of steam as fluidizing agent and prevents the possibility of unreacted steam in the product gas. That means that the moisture content in the product gas is reduced.

The experiments are performed in cylindrical fluidized bed with uniform diameter from bottom to top. A real bubbling fluidized bed gasifier has a coning design where the cross section area of the gasifier increases from bottom to top of the bed. The superficial gas velocity decreases with increasing diameter and consequently a suitable design of the gasifier can give uniform fluidization in the bed controlled by the inlet superficial gas velocity. According to the experimental results, bed materials with higher density remains on the bottom of the gasifier with lower cross sectional area whereas the mixture of bed material with char and wood particles with lower density are present mainly in the upper part of the bed with higher cross section area. The different cross section area should balance fluidization behavior in the bed. Real fluidization behavior of a gasification reactor should be studied using an optimal design of the cold bed to investigate a more realistic behavior.

4. Conclusion

Experiments are performed with ZrO and plastic beads with density 5850 and 964 kg/m^3 respectively. These particles have about the same density ratio as the char/wood and bed material in a fluidized bed gasifier. The experimental results can therefore give an indication of how mixtures of particles with different densities and particle size and shape may influence on the flow behavior in an actual gasifier. The fluidization properties and segregation tendencies are investigated for the pure ZrO and plastic particles and for mixtures of ZrO and 10, 20, 30 and 40 vol% plastic particles. The flow behavior for the different cases is studied by using pressure sensors and Electrical Capacitance Tomography (ECT). Average pressure drop over the bed is used to determine the minimum fluidization velocities (U_{mf}) for the different cases. U_{mf} is 0.85 and 0.67 m/s for pure plastic and ZrO particles respectively. Minimum fluidization velocity depends mainly on particle size, particle shape, particle density and void fraction. The plastic particles are rather large (2500-3500 µm), they have an irregular shape, low density and the initial void fraction is rather high (0.42). The ZrO powder consists of spherical particles with diameter 500-800 µm with high density and initial void fraction of 0.34. High density, high void fraction and large particles increase U_{mf}. The combination of the particle properties gives higher U_{mf} for the plastic beads than for the ZrO particles. The U_{mf} for the mixtures with ZrO and 10, 20, 30 and 40 vol% plastic particles are 0.75 m/s, 0.77 m/s, 0.70 m/s and 0.65m/s respectively. The U_{mf} has a maximum for the 20% mixture and decreases again with further increase in volume fraction of plastic. The theoretical U_{mf} based on Ergun equation is calculated for the different mixtures. The theoretical U_{mf} for the mixtures agrees well with the experimental results. The maximum U_{mf} occurs for a mixture of about 20% plastic beads. Pressure standard deviation is calculated to investigate the segregation tendency for the different mixtures. The results show that 30 and 40% mixtures give higher fluidization velocity in the lower than in the higher part of the bed. This indicates that the plastic particles moves upward in the bed and that mainly ZrO particles are present in the lower part of the bed. This is also visually observed during the experiments. Experimental results from ECT show the same tendency of segregation also for the mixtures with lower content of plastic beads. The ECT gives somewhat higher U_{mf} than the pressure sensors. All the experiments show that the bubble activity increases with height in the bed when the superficial velocity is increased above the $U_{mf.}$

5. References

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