Investigation of the segregation and mixing behavior of biomass in a bubbling fluidized bed reactor using a CPFD model

Rajan Jaiswal Nora C. I. S. Furuvik Rajan K. Thapa Britt M. E. Moldestad

Department of Process Energy and Environmental Technology
University College of Southeast Norway, Norway

rajanjaiswal357@outloook.com {rajan.k. thapa, nora.c.i.furuvik, britt.moldestad}@usn.no

Abstract

Segregation of biomass in a gasification reactor is an inevitable problem that can jeopardize the advantages such as uniform temperature control and proper mass circulation, and good solid-gas contacting area of the fluidized bed. This work investigates the mixing and segregation behavior of the biomass in a bubbling fluidized bed using a Computational Particle Fluid Dynamic (CPFD) model. The model is simulated in the CPFD software Barracuda VR. The sand particles and wood chips are used as the bed material and biomass. The simulations are carried out with different volume percentage of the biomass at constant bed aspect ratio. The results show that the minimum fluidization velocity is decreased from $0.08\ \mathrm{m/s}$ to $0.06\ \mathrm{m/s}$ with the increase in biomass volume from 5% to 20% in the bed. The complete segregation of biomass occurs at the superficial gas velocity that is 3.5 times greater than minimum fluidization velocity. With the increase in superficial gas velocity, $u_0 \geq 6.u_{mf}$, the biomass again starts to mix with the bed material. However, the mixing of woodchips is mainly limited to the upper part of the bed.

Keywords: fluidized bed, wood chips, segregation, mixing, CPFD, Barracuda, biomass gasification.

1 Introduction

Background

Increasing demand of environmentally friendly energy has compelled researches and industries to look for an alternative source of energy. Biomass gasification in a fluidized bed reactor is a promising technology, which delivers enormous advantages in terms of higher energy yield (environment friendly) producer gases, uniform thermal control and proper mass circulation, and good solid-gas contacting area. In the bubbling fluidized bed, the lower density large particles (biomass) are fluidized with the smaller solid particles (bed materials) with the fluidizing agent air or steam. For an energy efficient gasification, uniform mixing of the biomass with bed material and fluidizing gas is essential. However, the difference in densities and sizes of the particles inside the bed causes the particles to segregate. Thus, the advantages of fluidized bed can be compromised by the segregation of solids. The segregation of the biomass in the bed can be in axial or lateral direction depending on the biomass feeding location, density ratio, ratio of biomass to bed material, sizes of biomass and bed material, and fluidizing gas velocities (Nienow *et al.*, 1978; Zhang *et al.*, 2009; Thapa, *et al.*, 2011; Bandara *et al.*, 2018; Kraft *et al.*, 2018; Agu *et al.*,2019). Many researches have studied the segregation and mixing behavior in the gasification of biomass. However, discrepancy still exists in understanding the complex behavior of gas-solid interaction during segregation phenomenon in the gasification process.

Rowe *et al.*, 1972 termed the particles that float to the surface of bed as flotsam and jetsam to the particles that tend to sink to the bottom of the bed (Rowe, 1972). The drag force exerted by the fluidizing gas velocity determines whether the particles behave as flotsam or jetsam. Thus, the uniform mixing of biomass inside the bed depends on the segregation tendency and fluidizing gas velocity. The mixing tendency can be enhanced by increasing the bed agitation. In a bubbling fluidized bed, the intensity of the gas velocity to obtain proper mixing is limited to fact that the reactor must be operated within optimum bubbling regime for maximum efficiency. During gasification of biomass, the inlet fuel particle undergoes drying and devolatilization and are converted to char particles. The release of volatile gases reduces the density of the fuel particles. In addition, endogenous bubbles are formed by the devolatilization and drying of biomass particles, enhancing the segregation process. The endogenous bubbles, which envelop the biomass particles, tends to lift the biomass to the surface (Bruni, *et al.*, 2002; Chirone *et al.*, 2012) thus, reducing the gas exchange between the bubbles and the emulsion phase. The volatile matter bypasses the bed materials and are mostly released above the surface of the bed. Due to poor contact between volatile components and the fluidizing gas, the process can be inefficient. Also, it is likely, that the fine biomass particles that are segregated on the surface, burnout in the freeboard. The process of formation of endogenous bubbles from the fuel particles and segregation of particles in axial and lateral direction are shown in Figure 1. The bed material acts as the thermal flywheel in the gasification reactor. Thus, the contact duration of the biomass with bed materials determine the fluidization quality and stable operation of the process. During devolatilazation of biomass, tar components are released into the reactor. The formation of tar is strongly influenced by the operating parameters for instant temperature (Kinoshita and Wang,1994) and type of biomass used(Font Palma, 2013). The tar components may condense and form deposits on the downstream equipment that can lead to the complete shutdown of the operation. Therefore, it is essential to improve fluidization and proper mixing fuel particles for the reduction of tar formation(Rowe *et al.*, 1972; Kuba *et al.*, 2018).

Figure 1. Segregation of biomass in axial and lateral direction.

In this work, the segregation and mixing behavior of the lower density wood chips with sand particles are investigated using a CPFD model. The Computational model was validated against the experimental results. The results used to validate the model was the pressure drop and minimum fluidization velocities.

The CPFD model is used to study the segregation behavior in the bed. In order to investigate the mixing and segregation between the bed material and the wood particles, it is necessary to track the concentration/flow of the particles along the bed height. For this purpose, a number of flux planes are created in the CPFD model as shown in Figure 2 (a). Each of the flux planes are set to measure time integrated mass of the wood chips. The volume percentage of biomass inside the bed were varied to study its influence on mixing and segregation tendency.

2 Experimental and Simulation set up

2.1 Experiment

The experimental setup used in this work is the same as used by (Jaiswal and Agu, 2018) in his previous work. The experimental set up consists of a reactor of diameter 8.4 cm and height 140 cm. The pressure drop inside the bed due to change in superficial gas velocity is measured by the pressure transducers attached along the wall of the column. Experiments were carried out with the sand particles and biomass as bed materials at an aspect ratio (H/D) = 2.5. Where, H is the static bed height and D is the diameter of bed. Table 1 shows the properties of bed material and biomass (wood chips) used for this work.

Table 1. Particle properties

Particles	Desity, (ρ_p) $[kg/m^3]$	Solid volume fraction	Mean diameter (d_m) $[\mu m]$	Size range
Sand	2650	0.54	285	200-355
Biomass	423	0.44	N/A	5mm-0.5cm

2.2 Simulation set up

The Computational particle fluid dynamics software Barracuda VR uses the Multi- Phase Particle in Cell (MP-PIC) approach, where particles with similar properties such as diameters and densities are grouped together to form the computational unit of the computational particles termed as parcels. In this MP-PIC technique, combined Eulerian and Lagrangian methods are used for the modeling of gas-solid interaction. The fluid phase is solved with the continuum model, while the particle phase is solved using the Lagrangian method. The advantages of using CPFD approach compared to other CFD techniques is that it is cost optimal and saves computational time.

Figure 2. shows the simulation set up used for this work. A 3D geometry of height 140 cm and diameter 8.4 cm was imported to Barracuda VR and uniform grid of total cells 8640 were established around the geometry. The top of the reactor is open to the atmosphere and set as the pressure while the flow boundary condition is setup at the bottom of the reactor. The transient data points were selected along the height to monitor the pressure. The measuring points resemble the experimental setup. Different flux planes were assigned along the reactor to track the particle species passing through it during fluidization. The flux planes, transient data points, initial particles species, particle volume

fraction and pressure boundary conditions are shown in Figure 2 a-e respectively.

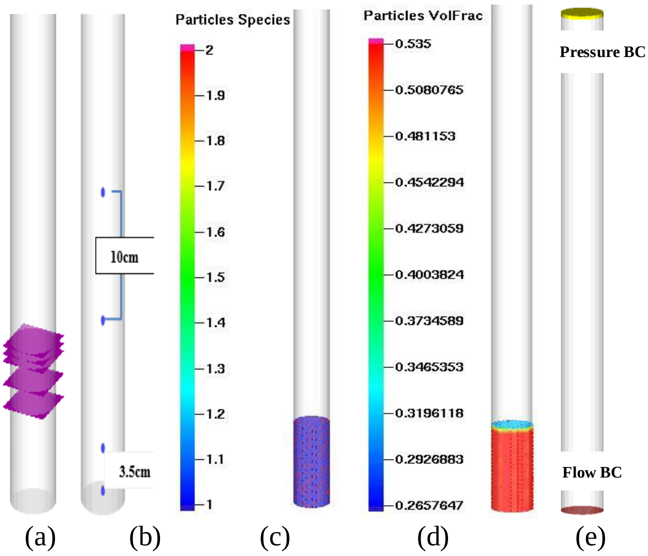


Figure 2. Computational setup showing (a) Flux planes, (b) Transient data location, (c) Particle species, (d) Particle volume fraction, (e) Pressure and flow boundary conditions**.**

The operating parameters used for the simulations are listed in Table 2. Air is used as the fluidizing agent at ambient conditions and the superficial gas velocity is increased gradually to obtain the fluidization properties of the mixture.

Table 2. Operating parameter

Temperature	300K
Pressure	101325 Pa
Superficial gas velocities	0.03-0.75 m/s
Maximum momentum redirection from collision	0.44 %
Normal to wall momentum retention	0.33
Tangential to wall momentum retention	0.99

3 Result and Discussion

3.1 Model Validation

The simulations are carried out with sand particles with mean diameter of 285µm at an aspect ratio of 2.5. The pressure drop is plotted against the superficial air velocities. The Wen and Yu drag model has been used for the simulation. The profile of pressure drop vs superficial gas velocities obtained from the CPFD model is compared with the experimental data as shown in Figure 3. The result shows that the simulation model fits well with the experimental data. Thus, this model is used for further simulations.

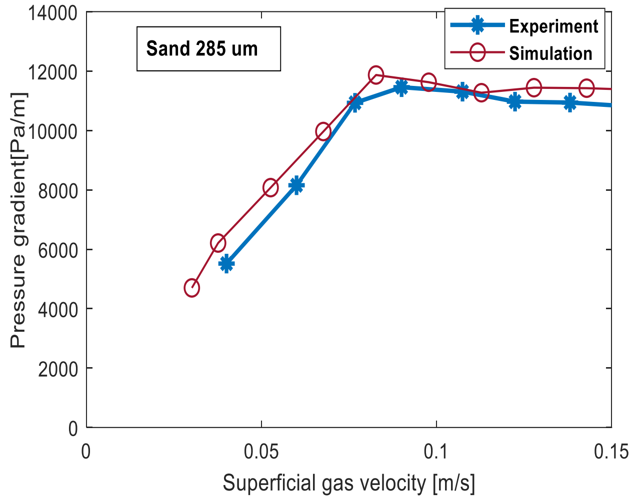


Figure 3. Pressure drop vs superficial gas velocity.

3.2 Minimum fluidization

The different volume percentage of biomass (5%, 10%, 15%, and 20%) were added to the initial static bed uniformly and the superficial gas velocities were increased gradually to investigate the fluidization behavior of the bed with biomass. Two sensors located inside the bed were chosen for the analysis. The result shows that the minimum fluidization velocity and pressure gradient decreases with increase in biomass volume inside the bed. The minimum fluidization velocity is found to be decreased from 0.08 m/s to 0.06 m/s with the increase in biomass from 5% to 20% inside the bed. The decrease in the pressure gradient is due to increase in the concentration of the lower density biomass inside the bed. The larger size biomass in the bed increases the void within the bed, making an easy passage of fluidizing air through the bed. Thus, the minimum fluidizing velocity decreases. The behavior of the biomass-sand mixture with the change in gas velocities is shown in Figure 4.

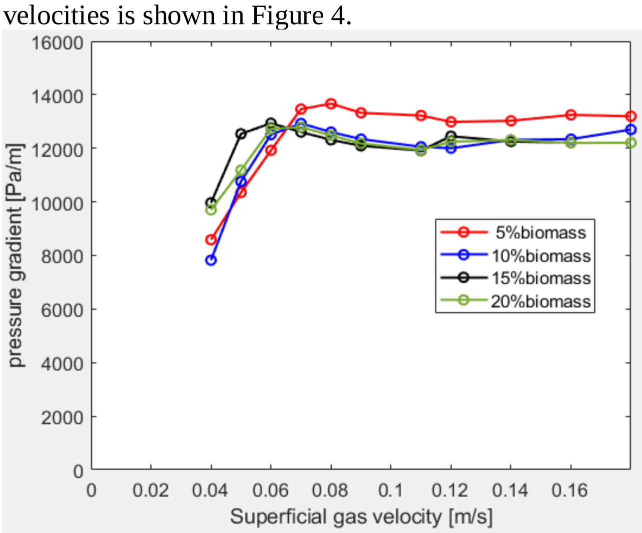


Figure 4. Pressure drop profile for the bed with different biomass percentage.

Figure 5 compares the minimum fluidization velocity obtained from the experimental data and the simulation. The results show that the simulation results are good in agreement with the experimental data.

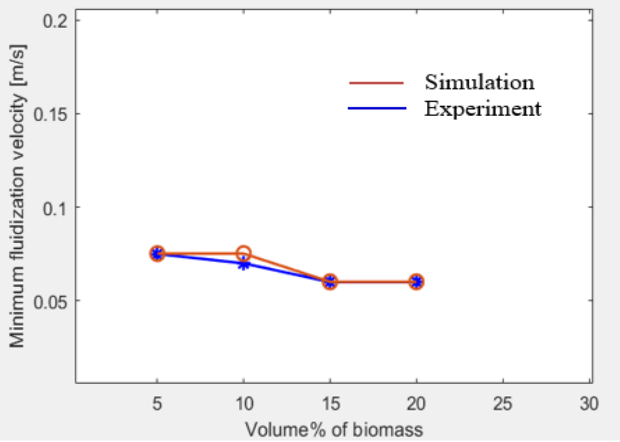
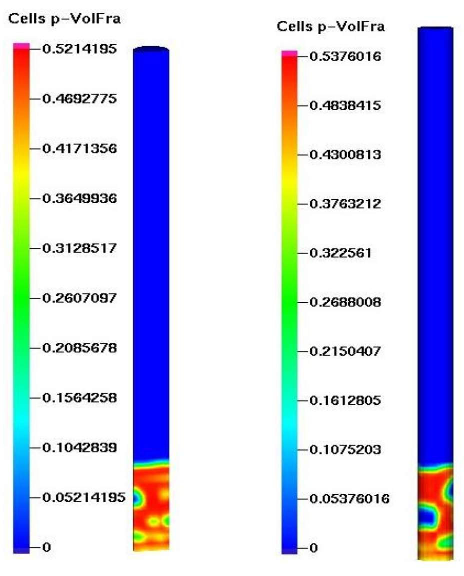


Figure 5. Minimum fluidization velocity of the bed with different biomass percentage obtained from experiment and simulation.

3.3 Bubble behavior

Figure 9 shows the Cell volume fraction of the particles in the bed with 20 % and 5% volume of woodchips. The cell particle volume fraction less than 30 percent represents the bubble inside the bed. The figure shows that the bubbles are larger and more distinct in the bed with 5% wood chips. With the increase in wood chips load to 20 volume % of the bed, the formed bubbles are smaller and most of the bubbles collapse within bed due to higher concentration of the irregular sized wood chips. The smaller bubbles inside the bed inversely affect the gas and solid interaction and mixing behavior of the bed.



(a) **(b)**

Figure 6. Cell volume fraction of the bed with (a) 20% volume of biomass (b) 5% volume of biomass.

3.4 Segregation of particles

Flux planes set at different locations in the reactor, as shown in Figure 2 (a), are used to monitor time integrated particle mass of species: biomass and sand particles passing through the planes at different gas velocities. Figure 7 shows the time integrated mass of biomass in upward direction at different fluidizing gas velocities when the bed is mixed with 10 % biomass and sand particles. The initial static bed height is 21 cm. One of the flux planes is set up on the top of the bed. The result shows that the biomass that are initially uniformly distributed across the bed starts to move in upward direction as soon as the bed is fluidized. The figure illustrates that the biomass remained at the bottom passes the flux planes at the heights 13 cm and 16 cm at the superficial gas velocity 0.12 m/s within 120 s. With the increase in gas velocity, the biomass segregated and accumulated above the flux plane at height 20 cm at the superficial gas velocity 0.18 m/s. The linear trend of the time integrated mass of biomass for the flux planes at 19 cm and 20 cm indicates that there is no biomass inside the after 200 s and at the corresponding superficial gas velocity of 0.2 m/s. The wood chips float at the upper region of the bed.

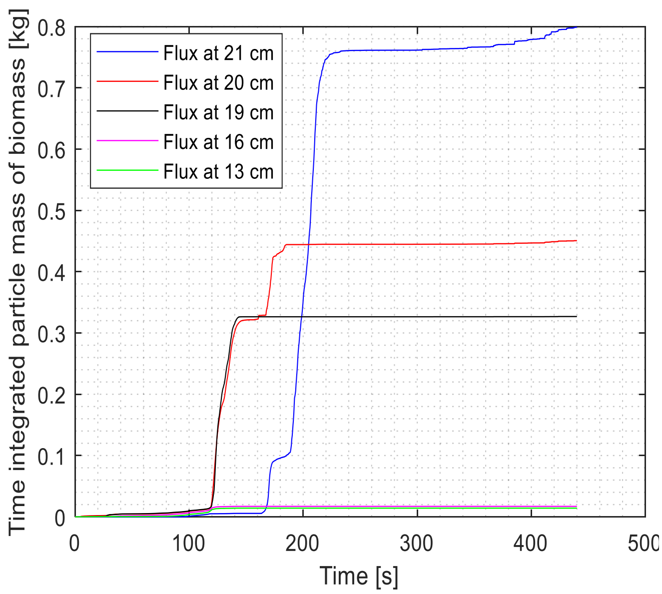


Figure 7. Time integrated mass of biomass across different planes with 10% (volume) biomass inside bed.

Figure 8 represents the segregation and mixing behavior of the wood chips in the bed. The figures are produced from the post processing tool available in Barracuda. At each time step, the behavior of biomass inside the reactor with change in gas velocities are analyzed. The particle species that are red in color are biomass while the blue color species are the sand particles. The biomass that remained at the upper part of the bed, segregated quickly and accumulated at the top of the bed. The segregation of biomass locally along vertical direction is shown in Figure 8 (a). This tendency of biomass to segregate inside the bed decreases the efficiency of the reactor since the biomass has not sufficient time for the gasification. In addition, the biomass might burnout in the freeboard reducing the overall efficiency of the process. The upward movement of biomass particles as shown in Figure 8 (a), has a ring like structure, suggesting that the movement of biomass inside the bed is mostly along the wall of reactor. The partial segregation and complete segregation of biomass are shown in Figure 8 (b) and 8 (c) respectively. The complete segregation occurs at gas velocity $u_0 \geq 3.5 \cdot u_{mf}$. Where, u_0 is the superficial gas velocity and u_{mf} is the minimum fluidization velocity.

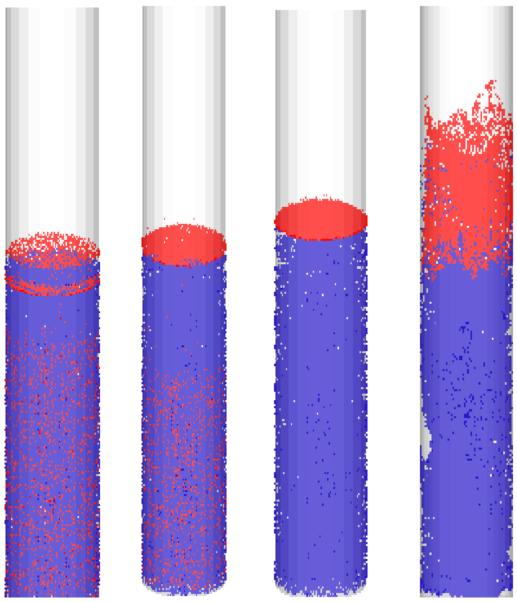


Figure 8. (a) Local segregation (b) partial segregation (c) complete segregation (d) mixing.

3.5 Mixing of wood chips

Figure 9 shows the mixing behavior of the bed with 20% volume of the biomass inside the bed. The result shows that the biomass starts to mix at the superficial gas velocity, $u_0 \geq 6 \cdot u_{mf}$. The mixing of biomass starts when the bed agitation is high enough to counterbalance the drag force that tends to lift the biomass in the upward direction. The increasing trend of the time integrated biomass particles at the flux planes at the height 21 cm and 20 cm as shown in Figure 8, explains the mixing of biomass inside the bed. The more biomass passing thorough the flux plane the more indication of mixing of wood particles with the sand in these parts of the bed. The quantity of biomass that are pushed inside the bed tends to move upwards, increasing the mass of biomass passing the flux plane. However, the mass of biomass through the flux planes below 20 cm is constant indicating that the biomass is segregated completely. This illustrates that the biomass mixing is only limited to the upper portion of the bed. With the increase in volume percentage of biomass inside the bed, the mixing starts earlier.

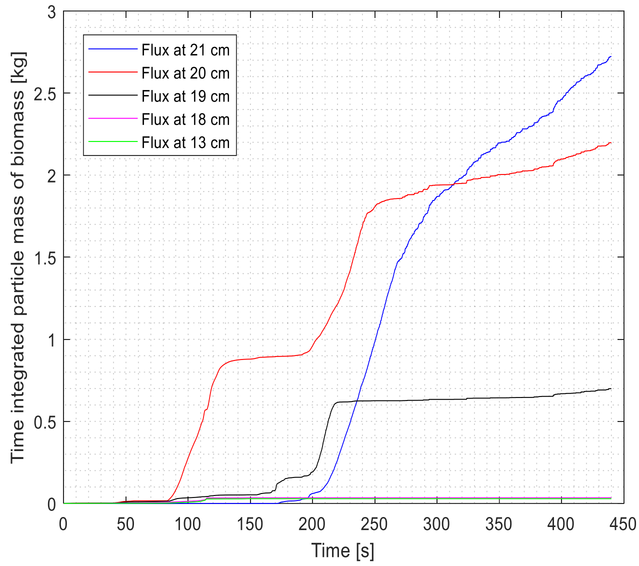


Figure 9. Time integrated mass of biomass across different planes with 20% (volume) biomass inside bed.

4 Conclusion

The difference in density, size, and ratio of bed material to biomass influences on the segregation and mixing tendency in gasification of biomass using fluidized bed. The segregation of biomass limits the advantages such as uniform thermal control and proper mass circulation, and good solid-gas contacting area of the fluidized bed. Therefore, it is crucial to study the segregation and mixing properties of biomass in the gasification.

This study investigates the mixing and segregation behavior of the biomass in a bubbling fluidized bed. Sand particles with mean diameter 285 μm and wood chips with size range $7mm - 0.5\ cm$ are used in the bed. A CPFD model is established in Barracuda VR. The model is validated against the experimental results. The simulations are carried in a reactor of diameter $8.4cm$ and height $140cm$. The biomass volume percentages 5%, 10%, 15% and 20% are used inside the bed at the constant aspect ratio 2.5. Flux planes at different heights are set up inside the reactor to capture the biomass behavior with the change in superficial gas velocities. The flux planes track the particle species along the bed heights.

The results show that the minimum fluidization velocity is decreased from 0.08 m/s to 0.06 m/s with the increase in biomass volume from 5% to 20%. The biomass starts to move upward as soon as it reaches the minimum fluidization velocity. The movement of the biomass are mostly along the wall of the reactor. The complete segregation of biomass occurs at $u_0 \geq 3.5 \cdot u_{mf}$. The mixing of biomass is only limited to the upper plane of the reactor and the segregated biomass starts to mix with the bed material at the superficial gas velocity $u_0 \geq 6 \cdot u_{mf}$.The formation and growth of bubbles are inversely affected by the increase in concentration of woodchips inside the bed.

The results presented with the CPFD model in this study enhances the understanding of the segregation and mixing phenomena in the fluidized bed. Also, the CPFD method presented in this work explores the possibilities to use it at the industrial scale gasification reactors.

References

C. E. Agu, L.-A. Tokheim, C. Pfeifer, and B. M. Moldestad Behaviour of biomass particles in a bubbling fluidized bed: A comparison between wood pellets and wood chips. *Chemical Engineering Journal*, 363: 84-98, 2019.

J. C. Bandara, R. K. Thapa, B. M. Moldestad, and M. S. Eikeland. Simulation of Particle Segregation in Fluidized Beds. In the *Proceedings of The 9th EUROSIM Congress on Modelling and Simulation, EUROSIM 2016, The 57th SIMS Conference on Simulation and Modelling SIMS 2016, Linköping University Electronic Press*.

G. Bruni, R. Solimene, A. Marzocchella, P. Salatino, J. Yates, P. Lettieri, and M. Fiorentino. Self-segregation of highvolatile fuel particles during devolatilization in a fluidized bed reactor. *Powder Technology*, 128(1): 11-21, 2002.

C. Font Palma. Modelling of tar formation and evolution for biomass gasification: A review. *Applied Energy*, 111: 129-141, 2018.

R. Jaiswal, C. E. Agu, R. K. Thapa, and B. M. Moldestad. Study of fluidized bed regimes using Computational Particle Fluid Dynamics, In *Proceedings of The 59th Conference on Simulation and Modelling (SIMS 59*), 26-28 September 2018, https://doi.org/10.3384/ecp18153271.

C. M. Kinoshita, Y. Wang, and J. Zhou. Tar formation Under Different Biomass Gasification Conditions, 1994.

S. Kraft, M. Kuba, and H. Hofbauer. The behavior of biomass and char particles in a dual fluidized bed gasification system. *Powder Technology*, 338: 887-897, 2018.

M. Kuba, S. Kraft, F. Kirnbauer, F. Maierhans, and H. Hofbauer. Influence of controlled handling of solid inorganic materials and design changes on the product gas quality in dual fluid bed gasification of woody biomass. *Applied energy, 210: 230-240*, 2018.

A. W. Nienow, P. N. Rowe, and T. Chiba. Mixing and segregation of a small proportion of large particles in gas fluidized beds of considerably smaller ones. *AIChE Symp* Ser, 74(176): 45-53, 1978.

P. Rowe. The mechanisms by which particles segregate in gas fluidised beds-binary system of near spherical particles.*Trans. Inst. Chem. Engng*, 50: 310-323, 1972.

P. N. Rowe, A. W. Nienow, and A. J. Agbim.The mechanism by which particles segregate in gas fluidized bedsbinary systems of near-spherical particles. *Trans. Inst. Chem. Eng.*, 50: 310-323, 1972.

R. Solimene, R. Chirone, and P. Salatino. Characterization of the devolatilization rate of solid fuels in fluidized beds by time-resolved pressure measurements. *AIChE Journal*, 58(2): 632-645,2012.

R. K. Thapa, C. Rautenbach and B. Halvorsen. Investigation of flow behaviour in biomass gasifier using Electrical Capacitance Tomography (ECT) and pressure sensors. Rautenbach, C. *An Experimental and Theoretical Study of Dense Fluidized Bed Fluid Dynamics. PhD Thesis, Telemark University College*, 2012.

Y. Zhang, B. Jin and W. Zhong. Experimental investigation on mixing and segregation behavior of biomass particle in fluidized bed. Chemical Engineering and Processing: *Process Intensification*, 48(3): 745-754, 2009.