CHEMICAL ENGINEERING TRANSACTIONS
VOL. 56, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Jiří Jaromír Klemeš, Peng Yen Liew, Wai Shin Ho, Jeng Shiun Lim

ISBN 978-88-95608-47-1; **ISSN** 2283-9216
DOI: 10.3303/CET1756314

Computational Modelling of Gas-Solid Hydrodynamics and Thermal Conduction in Gasification of Biomass in Fluidized-Bed Reactor

Ramin Khezri*, Wan Azlina Wan Ab Karim Ghani

Dept. of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
ramin.khezri@gmail.com

A computational fluid dynamic model is developed to describe the fluid–particle interaction inside a fluidised bed reactor. The proposed gasifier reactor is 5 kW self-sustaining fluidised bed with 500 mm height and 127 mm diameter.The selected feedstock is ground Napier grass with particle diameter of 500 µm. The biomass particle is initially patched into the reactor and the hydrodynamic of the gas-solid fluidisation is modelled. The Eulerian approach is used to model the distribution of the mixture. Heat transfer from the surface of the biomass particle through the interior section is modelled according to the literature. ANSYS FLUENT 16.1 has been used as the modelling framework for the simulations.

1. Introduction

Biomass gasification can be the key in turning underutilised biomass into clean and sustainable energy, having several benefits over traditional sources of electricity (Mustafa et al., 2015).Thermochemical biomass gasification is a recognised technology and has been developed for variety of industrial applications. The conversion of biomass into hydrogen-rich gas seems to be a suitable source for energy production regarding its advantages e.g. renewable energy, sustainability, environmental friendly characters such as low amount of CO_2 emissions.

The hydrodynamics of fluidised-beds have been extensively investigated both experimentally and through various computational modelling. An experimental study proposed by Azlina et al. (2011) investigated gasification performance in terms of quality of the producer gas in optimised process condition, studied several effects of parameters e.g. feedstock origin, reactor design and operating parameters such as temperatures, equivalence ratio, static bed height, fluidisation and others. Another experimental study conducted by Khezri et al. (2016) investigated the effect of gasification parameters such as temperature and equivalence ratio on synthesis gas quality in terms of composition and yield, the study evaluates the comparison based on two different scales of reactors. So far, a numerous computational research interest has been focused on the simulation of the fluidisation hydrodynamics which mostly are using either the Eulerian (Pain et al., 2002) or the Lagrangian (discrete element) model. A two dimension computational fluid dynamics model using Eulerian multiphase flow model coupled with a population balance model (CFD-PBM) was developed in two different studies by Akbari et al. (2015a), to study the effect of using different air distributors in forming different fluidisation structure at entrance region in an industrial-scale gas phase fluidised bed reactor. Later in another study he investigated the effect of particle size distribution in an industrial gas phase polymerisation reactor by means of a CFD–PBM coupled model (Akbari et al., 2015b). The effect of different gas-solid drag models in a high-flux circulating fluidised bed riser has been studied by Armellini et al. (2015) using a two-phase CFD model in three dimensions, wherewith the correlations between several drag models were later verified through comparison of simulation results with the experimental data. The model predicted all correlations for solids concentration within the developed flow region of the riser, however at the level close to the inlet due to the high concentration of the solids, there seems that the Gidaspow and Syamlal-O'Brien models can poorly represent the solid volume fraction to the amount found experimentally.

Please cite this article as: Khezri R., Ghani W.A.W.A.K., 2017, Computational modelling of gas-solid hydrodynamics and thermal conduction in gasification of biomass in fluidized-bed reactor, Chemical Engineering Transactions, 56, 1879-1884 DOI:10.3303/CET1756314

In a study conducted by Arora et al. (2015), a kinetic-based model developed by using ASPEN Plus for a Dual Fluidisation Bed Gasifier to investigate the reactions governing in devolatilisation, catalytic and homogenous gasification which targets to produce synthesis gas and Tar.
With noteworthy increase of the computer power and the accuracy of calculations these days, the modelling of multiphase granular flows are seems to be easier to develop and hence more feasible is the development of reactor units in industrial scales. The self-sustaining fluidised bed reactor was chosen in this study due to fuel flexibility, high efficiencies and uniform heating.
In the current study the hydrodynamics of fluidisation for a mixture of biomass and sand particles is modelled and the results shows capability to investigate the affecting parameters such as minimum fluidisation velocity, maximum bed height to find the most effective biomass particle size. The second part of the study comprises the computational model for the heat diffusion from the surface of a single solid particle into its inner section while the particle is receiving a constant bed to surface heat flux from the fluidising medium.

2. Model description

2.1 Model description for fluidisation hydrodynamics

The 5 kW self-sustaining lab scale reactor is illustrated in Figure 1. The shape of the reactor is circular with dimensions as shown in Figure 2 and heating of bed medium is applied by blowing air from the bottom of the gasifier. The area which is initially patched with solid particles i.e. a mixture of sand and biomass particles in ratio of 1 : 1, is involving the 40 % of the reactor volume.

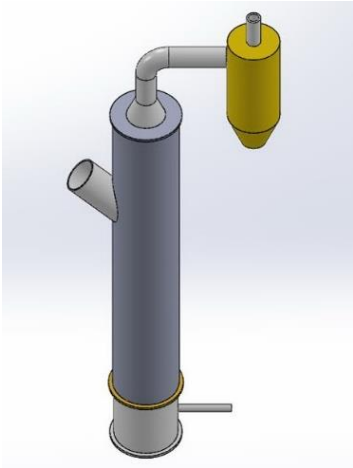

Figure 1: Schematic geometry of the gasifier

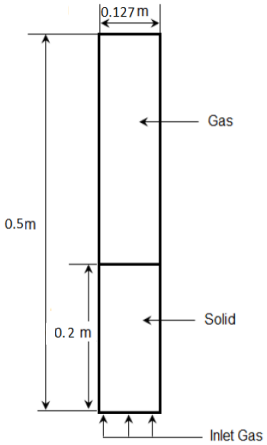

Figure 2: Dimension of the gasifier

Air as gasifying agent flows through a porous plate at the bottom of the reactor at different velocities is shown in Figure 3. The superficial velocity is roughly 4 times greater than the minimum fluidising velocity U_{mf} of the reactor, which is calculated through pressure-based method for the utilising device and investigated to be 0.06 m/s using a sand bed with average particle diameter of 420 µm which is classified in B Group (Geldart, 1973).
The biomass particles are fluidised as well as sand bed and the momentum is transferred from the bubbling bed to the biomass. The most suitable biomass particles sizes for synthesis gas production is between
0.01 - 0.6 × 10^{-2} m with temperature between 700 K and 800 K (Bridgwater, 1999). Therefore, the average biomass particle chosen for this study is 500 µm.
Table 1 shows the simulation parameters and model description variables. Different air velocities has been assigned while considering zero initial velocity for the solid particles and constant density of 1,225.76 kg/m^3 which is calculated for the mixture of sand and biomass with ratio of 1 : 1 and through Eq(1)

$$\rho_t = \frac{1}{2}\left(\rho_{biomass}\right) + \frac{1}{2}\left(\rho_{sand}\right) \quad (1)$$

Where ρ_t, $\rho_{biomass}$, and ρ_{sand} are the total density, density of biomass and sand respectively.

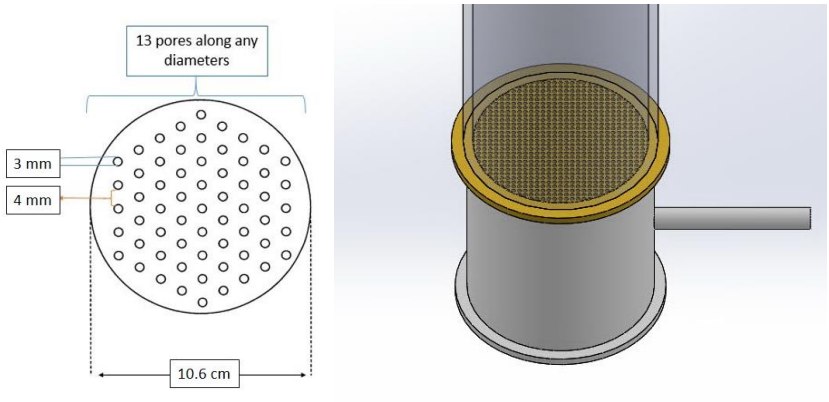

Figure 3: Porous plate air distributor

Table 1: Simulation parameters and model description

Model descriptions	Comment
Multiphase model	Eulerian
Viscous model	laminar
Drag model	Syamlal-O'Brien
Primary phase	Air
Secondary phase	Granular biomass solid-Sand particles (1 : 1)
Simulation parameters	**Values**
Inlet air flow rate	0.07 - 0.3
Density of Napier grass	817.53 kg/m³
Density of sand	1,634 kg/m³ (dry sand)
Specific heat capacity	2,500 J/kg.K

2.2 Heat transfer model

The heat conduction along the radius of the spherical particle is calculated by Fluent 16.1 considering the heat diffusion equation for an isotropic particle. The heat transfer coefficient is evaluated from (Ranz et al., 1952). A conductive heat flux of 1,023.15 K from the fluidising media is dominant to the surface of the particle and the inner layers of the biomass particle has the thermal conductivity of 0.2 $Wm^{-1}k^{-1}$ according to (Ramanaiah et al., 2012) for the ground Napir grass. The scope of the simulation is to determine the correct heat transport inside the biomass particle.

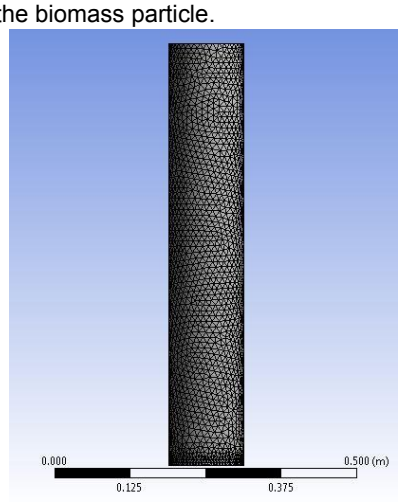

Figure 4: Mesh generated in finite element analysis

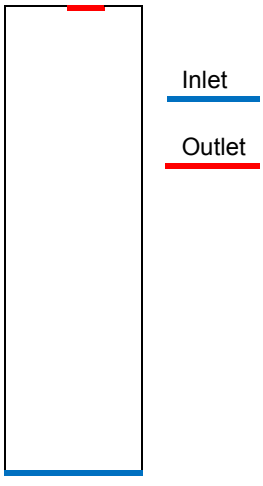

Figure 5: Boundary conditions

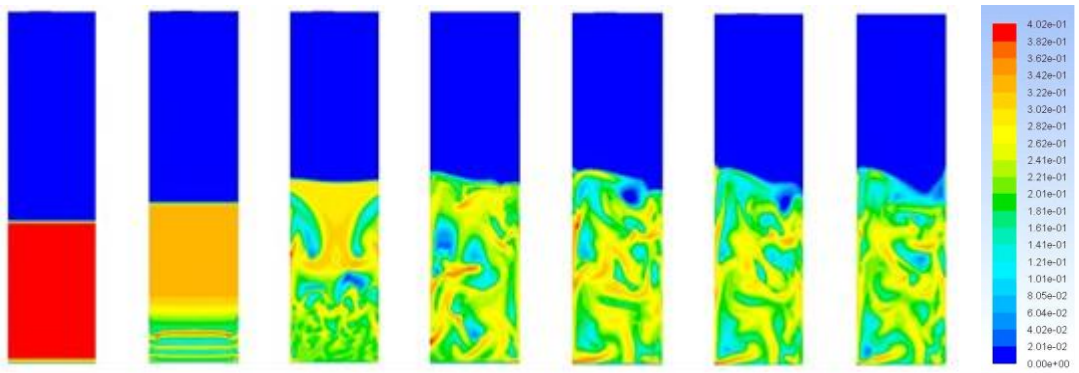

Figure 6: Solid volume fraction contour at air velocity of 0.07 m/s

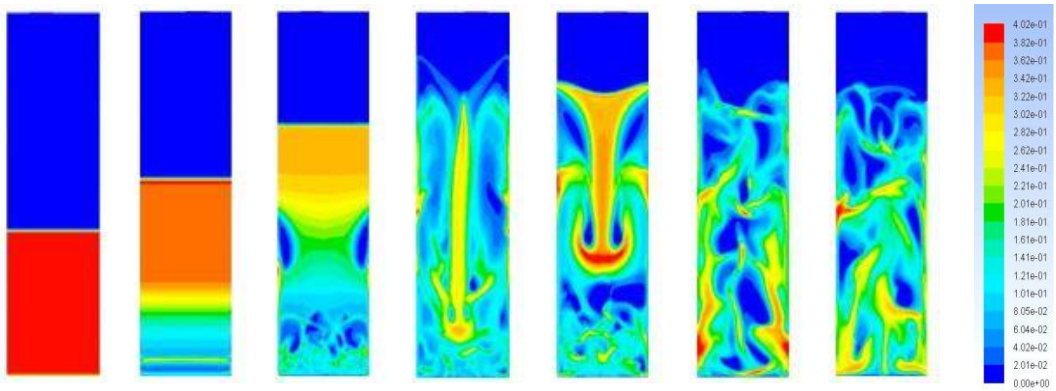

Figure 7: Solid volume fraction contour at air velocity of 0.2 m/s

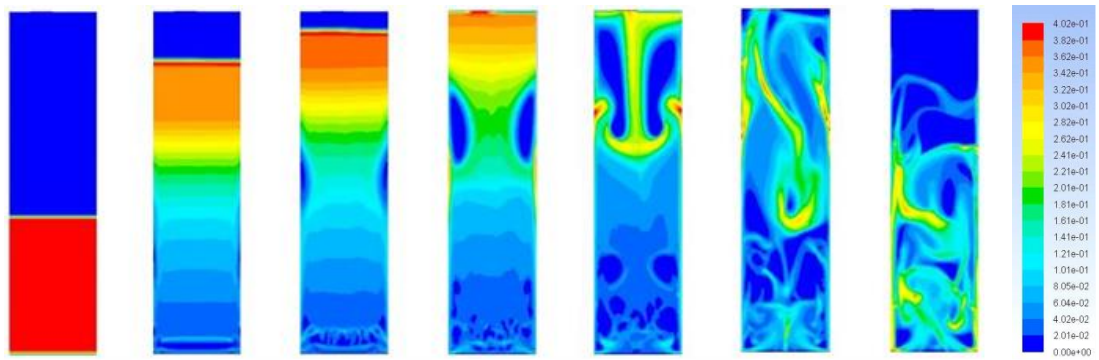

Figure 8: Solid volume fraction contour at air velocity of 0.3 m/s

3. Results and discussions

3.1 Numerical Results for fluidisation hydrodynamics

The mesh of the reactor is illustrated in Figure 4 for the 2D simulation of Eulerian fluidisation, with 16,000 elements and the momentum transport equations are calculated for 16,315 nodes. The boundary conditions (Figure 5) are set as follows: the wall conditions are fixed at no slip with no shear stress at any directions and thermally isolated; the bottom surface of the reactor has the inlet air at different velocities and zero velocity for solid particles; the ambient air temperature and pressure are set to the reference values; the outlet surface on top of the reactor is in absolute pressure with no backflow pressure defined. Thermodynamic equations for this part of simulation has not been solved and hence modelled in a separate study. The model has been developed for a pressure based transient time system using an Eulerian multiphase model with two phases of gas and granular solids.

Figures 6 to 8 illustrate the contours of solid volume fraction with 3 different velocities during the 3 s of the fluidisation. The colour map is showing the distribution of solid particles inside the reactor volume.
Figure 7 shows that air velocity at 0.2 m/s showed maximum bed expansion and the solid particles were fluidising in gasification region compared to the air velocity of 0.07 m/s (Figure 6) the medium showed to be minimum fluidisation. On the contrary, at 0.3 m/s the excess drag force from the air fluid caused the solid particles to travel further than expectation and hence escape from the reactor. The process of fluidised bed gasification is regarded to the degradation of the solid particles where the gasification chemical reactions take place to produce the hydrocarbon products and synthesis gas at the final stage. As conclusion, the largest bed expansion and highest gasification region the inlet air velocity of 0.2 m/s revealed that the solid particles has the most kinetic energy contents which will consequently have an intense effect on the yield of the final products.

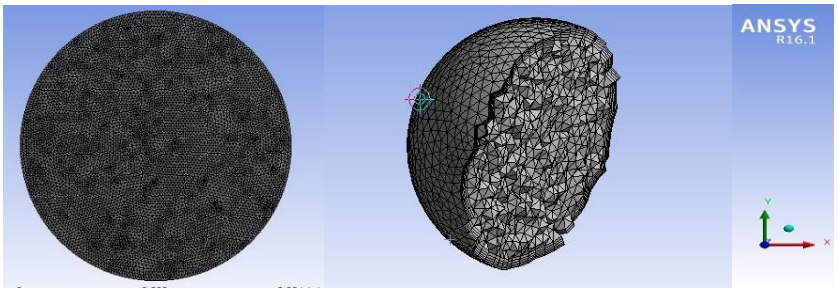

Figure 9: Mesh generated for single biomass particle

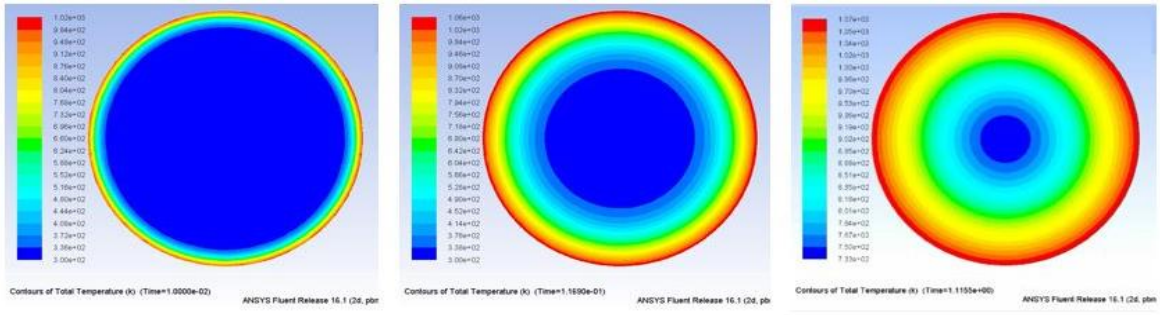

Figure 10: Heat conduction inside a single biomass particle

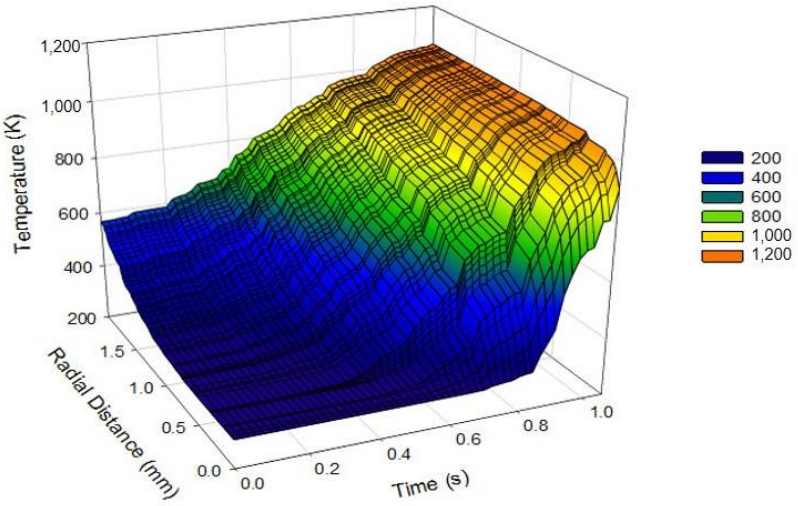

Figure 11: Radial heat transfer inside a biomass particle

3.2 Numerical Results for heat transfer model

The generated mesh for a single spherical solid particle with diameter of 500 μm is illustrated in Figure 9 and the conduction heat transfer contour for the outer surface temperature of 1,073.15 K and interior initial temperature of 300 K has been shown in Figure 10. The particle reaches the reactor temperature in approximately 1.1 s, while during the actual process, the exothermic reactions take place in gasification zone and make the internal section of the particle to reach a slightly higher temperature from its value within the reactor. Nevertheless, this temperature difference is mostly up to 2 K and is not easy to notice, therefore it can be considered insignificant and disregarded from the calculations (Papadikis et al., 2008).

The radial temperature distribution is shown in Figure 11. The surface plot shows the different temperature profiles inside the particle for different times during gasification. In actual gasification process, due to degradation, the density of the particles as well as their thermodynamic properties change and the heat transferred is considerably affected. The radial temperature profile seems to be fairly flat which can be due to the small biomass particle size with an average heat transfer coefficient of 350 m^2K.

4. Conclusion

Computational models developed and the fluidisation hydrodynamics of Napier grass gasification as well as conduction heat transfer inside a single biomass particle was modelled. From the hydrodynamic model, it was investigated that within various ranges of inlet air velocity, the amount of 0.2 m/s is proved to be the most significant value for the best performance. Drag force has been calculated from Syamlal O'Brien model and the density of the particles during gasification was considered constant, hence none of the effects of biomass degradation has been considered in study of fluidisation.

The heat transfer from the surface of a single biomass particle through its interior has been modelled and plotted and calculated the time to which the particle reaches the gasifier temperature is around 1.1 s and from there the degradation will be taking place.

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