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CFD Analysis on Fluidized Bed Gasification of Rice Husk and Rice Straw

Singh Pushpendra, A. K. Srivastava*

Department of Mechanical Engineering, Shri Ramswaroop Memorial College of Engineering and Management, Lucknow, India
Email: sspushpendra44@gmail.com, *ak_srmcem@rediffmail.com

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Abstract

In the work being presented, computational fluid dynamics (CFD) analysis on fluidized bed gasification of rice husk has been carried out. The multiphase Eulerian model was undertaken in the analysis. Due to the lack of computational space, two dimensional models of fluidized bed were created. The objective of the investigation was to study the effect of variation on velocity with varying particle sizes. The quality of synthesis gas was also taken into account. The inlet's superficial velocity was varied from 0.2 m/s to 1.2 m/s and diameter of rice husk varied from 0.0438 mm to 4.38 mm. Based on obtained results, this may be concluded that minimum fluidization velocity decreases with increase in diameter of rice husk. The carbon conversion was found to be maximum for 0.7 m/s velocity and carbon conversion increased for other velocities up to 96.9%. The analysis was carried out using ANSYS FLUENT 14.0 non-commercial code.

Subject Areas

Mechanical Engineering

Keywords

Computational Fluid Dynamics, Fluidized Bed, Eulerian Model, Superficial Velocity, Carbon Conversion

1. Introduction

The study of gasification of materials using fluidized bed [1] gasifier has been a subject of interest among many researchers and scientists. This problem is very much important in replacing fossil fuels, particularly the fuels used in automobiles. The gasification in general is referred to a process which converts organic or fossil fuels based carbonaceous materials into CO, CO_2 and *H* by reacting material at high temperature (>700˚C), resulting into syngas which is itself a fuel. Literatures reveal that many researchers have performed the study on temperature, agglomeration and computational space, but insufficient progress has been reported on the effect of inlet superficial velocity and particle size of material. The key issue is to address the dependence of carbon conversion on the two aforementioned parameters. The previous studies by Ravi Inder Singh [2], 2010, developed the mathematical model for minimum fluidization velocity, causes of agglomeration and visualization of flow pattern; K G Mansaray *et al.* [3], 2000, developed the model that was based on material balance, energy balance, and chemical equilibrium relations. A CFD model for fluidized bed biomass gasifier is developed and the simulations are carried out to obtain the optimal condition for production of hydrogen rich gas (Zhou *et al.*, [4], 2006). A non-premixed combustion model was used for biomass air-steam gasification in the gasifier. The simulation results were compared with the experimental data. The effects of the steam to biomass ratio (S/B), the equivalence ratio (ER), and the size of the biomass particles on the hydrogen yield were studied. A 2-D Eulerian multi-fluid approach for gas-solid system in a CFB was carried out for simulation where Kinetic theory of granular flow (KTGF) had been used for describing the particle phase and K-ε based turbulent model had been used for gas phase (Yanping *et al.*, [5], 2009). The model was used for the examination of the effects of the feeding configuration on the gas/solid two-phase flow, gas fluidization of solid particles (Toomey R. and Johnstone H. F., [6], 1952). The relaxation time of the bed was determined by the heat capacity of the fluidized solids and by the fraction of the heat released recycling to the bed as thermal feedback (Galgano *et al.*, [7] and Boroduyla *et al.*, [8]). Henceforth, in this work, the superficial velocity at inlet and the size of the particle are under consideration, which in turn affects the carbon conversion comprehensively. The simulations were run on the two-dimensional model using the Eulerian two phase models, solving the governing equations with the aid of ANSYS FLUENT CFD code (14.0). The obtained results can be served as a useful source material for future analytical and experimental investigations.

2. Methods

The entire work is focused upon the numerical simulation of two dimensional geometry of the fluidized bed gasifier. The process of analysis includes geometry modeling, discretization of computational domain, material selection, boundary conditions and then solver to run the calculations. The geometry modeling and discretization of computational domain was done on GAMBIT 2.2.30. Further simulation and post activities were run on non-commercial CFD code of FLUENT (ANSYS 14.0). The results fetched were then exported to plot the graphs and then compared to the previous works and the conclusions were drawn.

3. Modeling

The geometry size for the fluidized bed was taken from work of Ravi Inder Singh [2]. The vertical cross section of the bed was taken, the height of bed was 100 cm and the width was 28 cm. The geometry was in two parts; one assumed having the rice husk/straw of height up to 40 cm and remaining having fluid (air).

The air at different velocity is assumed to be entering the gasifier from the bottom at the constant given value. The geometry can be seen in above Figure 1.

The governing equations:

The Eulerian-Eulerian method is adopted for this study. The governing equations for the conservations of mass, momentum, energy and species transfer are given below [9]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v}\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\partial \vec{v}\right) + \nabla \cdot \left(\rho \vec{v}\vec{v}\right) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}}\right) + \rho \vec{g} + \vec{F} \tag{2}$$

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\alpha_q \rho_q h_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{u}_q h_q\right) \\ &= \alpha_q \frac{\partial P_q}{\partial t} + \bar{\bar{\tau}} : \nabla \vec{u}_q - \nabla \vec{q}_q + S_q + \sum\nolimits_{p=1}^{n}\left(Q_{pq} + \dot{m}_{pq} h_{pq} - \dot{m}_{qp} h_{qp}\right) \end{aligned} \tag{3}$$

$$\frac{\partial}{\partial t}\left(\rho Y_i\right) + \nabla \cdot \left(\rho \vec{v} Y_i\right) = -\nabla \cdot \vec{J}_i + R_i + S_i . \tag{4}$$

Inter phase drag:

$$C_D = \frac{D}{\frac{1}{2}\rho_q \left(v_q - v_p\right)^2 A}. \tag{5}$$

Lift force:

$$F_C^L = r_d \rho_c C_L \left(v_d^* - v_C^*\right) \times \left(\omega_c^* + 2\Omega\right). \tag{6}$$

Laminar finite rate model:

The laminar finite-rate model computes the chemical source terms using Arrhenius expressions, and ignores the effects of turbulent fluctuations [10]. The net source of chemical species "*I*" due to reaction is computed as the sum of the Arrhenius reaction sources over the N_R reactions that the species participate in and is given as:

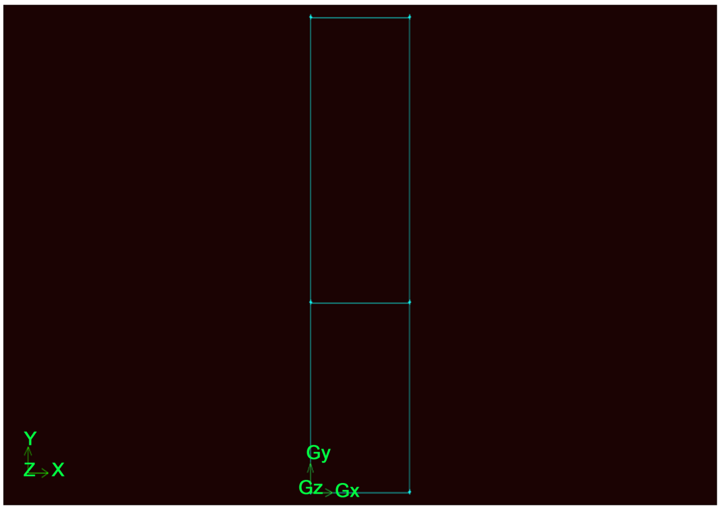

Figure 1. Geometry (as in GAMBIT).

$$R_i = M_{w,i} \sum_{r=1}^{N_R} \hat{R}_{i.r}. \quad (7)$$

The forward rate constant for the reaction r, $k_{f,r}$ is computed using Arrhenius expression:

$$k_{f,r} = A_r T^{\beta r} e^{-E_r/RT}. \quad (8)$$

4. Analysis

The Fluent 14.0 program was chosen for the numerical simulation. Prior to simulation in fluent the grid size was set for the computational domain. The two boundary continuums were set namely, bottom area and top area. The bottom area consists of rice husk/straw and the top area consists of air. Based on these, the grid sizes were set; the top area has fine mesh (as it has air in initial condition) as compared with the bottom area, which is having rice husk/straw. The uniformed quadrilateral cells were developed.

Total nodes = 281,281.

Total quadrilateral cells = 280,000.

For solving the equations, Phase Coupled method was used and first order upwind was implied for all the equations. Since the flow was multiphase, Eulerian-Eulerian method was used where both gas and solid phases were treated as continua, inter-penetrating and interacting with each other everywhere in the computational domain. The single pressure field is assumed to be shared for all phases, in proportion to their volume fractions. The motion of each phase is governed by their mass and momentum conservation equations.

The following conditions were used (Table 1).

Biomass gasification is a multiphase problem between gases and rice husk particles. It is also a reactive flow that involves homogeneous reactions among gases and heterogeneous reactions between rice husk particles and gases. In this study, both gas phase (Phase 1) and rice husk phase (Phase 2) are solved by using Eulerian multiphase model. The gas phase is used for simulating both the steam inlet and the product gas outlet. This is achieved by including all the working species in one phase so that the mass and momentum equations are solved once per time

Table 1. Boundary conditions and other criteria.

Flow type	Laminar
Granular viscosity model	Constant
Drag model	Syamlal-obrien
Frictional viscosity model	Schaeffer
Heat	Gunn
Number of iterations per time step	80
Convergence criterion	0.0001
Particle-particle restitution coefficient	0.90
Inlet velocities [11]	0.2, 0.7, 0.9, 1.2 (m/s)
Outlet condition	Atmospheric pressure

step. It consists of O_2, N_2, H_2O, H_2, CO, CO_2 and CH_4. The properties of the species are taken from Ansys Fluent database. The gasifying agent is air considered at a constant velocity. Rice husk is considered as the feed material in this study. It is considered to be a granular phase. It consists of solid carbon (*C*) representing char, H_2O for the fuel's moisture and CH_4 for the volatile matter (**Table 2**).

Eulerian multi-fluid model is adopted [12] [13] [14] where gas and solid phases are all treated as continua, interpenetrating and interacting with each other everywhere in the computational domain. The finite rate model is considered. Finite rate model is used to predict the reaction rate. The discretization scheme for momentum, energy and species all has been taken as first order upwind. For volume fraction of solid and gas phase Quick scheme is used.

5. Results & Discussions

The simulation was run on Fluent to obtain the results. The graphs for velocity variation along the height of bed were plotted. Different diameters of rice husk for same velocity were simulated and also the variation in velocity was also observed keeping the diameter of rice husk same. The superficial velocities 0.2 m/s, 0.7 m/s, 0.9 m/s and 1.2 m/s were run and diameters 0.0438 mm, 0.438 mm and 4.380 mm were tested.

Now as we go through the graphs, the point from where the curve starts to attain minimum fluctuation that is starts to be constant, the velocity of Phase 2 at that point is called minimum fluidization velocity.

In **Figure 2**, the superficial velocity or inlet velocity is equal to 0.2 m/s. It is evident from the curve that fluidization velocity of rice husk decreases with increase in the size of particle, the minimum fluidization velocity decrease from approx 2 m/s to 1.5 m/s. Similarly, in **Figure 3**, the superficial velocity is 0.7 m/s and it is evident that same trend of decrease in minimum fluidization velocity with increase in size of rice husk particle is found. It decreases from approx 2.75 m/s to 1.25 m/s for variation in particle diameter from 0.0438 mm to 4.38 mm.

The similar trend of decreasing of minimum fluidization velocity with increase in diameter of rice husk particle is found as it is well depicted from plots. The superficial velocities in **Figure 4** and **Figure 5** are 0.9 m/s and 1.2 m/s respectively. However, if go across the variation in inlet superficial velocity and keeping the diameter of rice husk particle constant, it was the was no particular trend in

Table 2. Species mass fraction in rice husk and air.

Species mass fraction	Rice husk	Air
H_2O	0.0734	
C (s)	0.2046	
CH_4	0.5640	
N_2		0.23
O_2		0.77

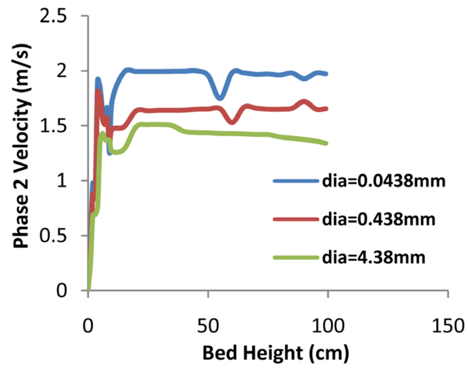

Figure 2. Inlet velocity = 0.2 m/s.

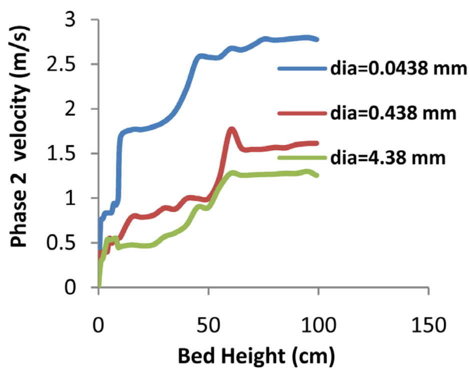

Figure 3. Inlet velocity = 0.7 m/s.

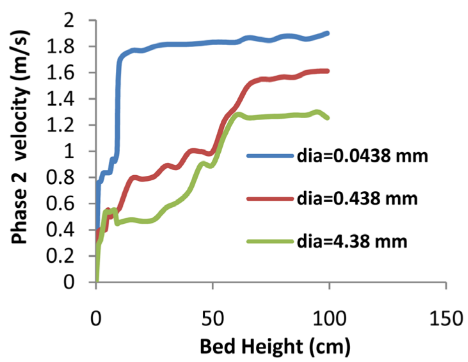

Figure 4. Inlet velocity = 0.9 m/s.

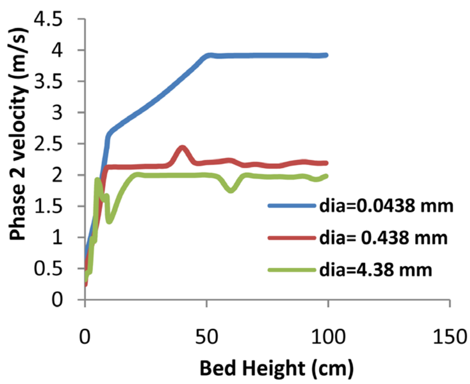

Figure 5. Inlet velocity = 1.2 m/s.

the minimum fluidization velocity as it firstly increase then decreases and then again increases. This is well evident from curves obtained as shown in Figures 2-4.

Also the velocity of phase 2 particles is also found to be zero at the wall of the gasifier and is maximum at the center line along which the graphs have been plotted.

The region near the fuel inlet shows a particularly concentrated region for the gaseous species of CO, H_2 and CH_4. This region signifies the accumulation of devolatilisation products as the fuel is introduced to the bed at this point. The products then mix through the bed along with the products of heterogeneous reactions from the lower bed region to continually trigger further reactions.

The simulation results are compared to the actual experimental data. It is noticeable that N_2 and CO_2 are overestimated, while H_2 is underestimated as shown in Figure 6. The CO and CH_4 mass fractions show acceptable agreement with the experimental data taken from [2] and [15] *i.e.*, study by Ravi Inder Singh, 2010, where the mathematical model for minimum fluidization velocity, causes of agglomeration and visualization of flow pattern was being done and by Ramirez, 2007, where gasification was done on pilot scale.

6. Conclusions

Based on the results obtained from simulation, following conclusions were drawn:

1) Increasing the inlet superficial velocity makes the flow development faster and has a strong influence on the velocity of rice husk.
2) The velocities of the smaller particles are larger than those of the bigger particles in the lower zone due to the attainment of high slip on the bottom side.
3) The minimum fluidization velocity increases with decrease in the diameter size of rice husk particle and *vice-versa*.
4) There is no specific trend followed when superficial velocity is varied and diameter of rice husk particle is kept same; it may increase or decrease as observed.

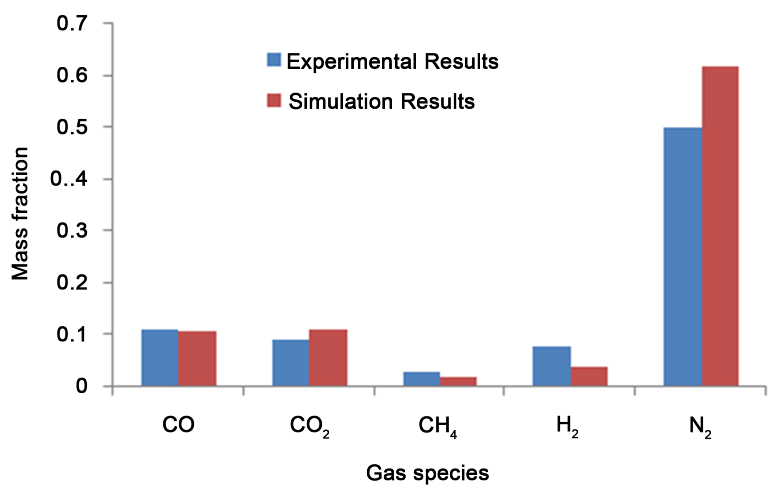

Figure 6. Experimental and simulation results.

5) The reactions in the instantaneous gasification model occur very fast and finish very quickly with an indicating 100% carbon conversion for superficial velocity 0.7 m/s and can be increased up to 96.9% for other considered superficial velocities.

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Nomenclature

α	Volume Fraction
ρ	Density of Fluid (kg/m^3)
v	Velocity (m/s)
p	Pressure (Pa)
$\overline{\overline{\tau}}$	Stress-strain Tensor (Pa)
$\vec{g}$	Acceleration due to Gravity (m/s^2)
μ	Viscosity (kg/m·s)
h	Specific Enthalpy (J/kg)
q	Heat Flux (J)
∇	Gradient
β	Coefficient of Thermal Expansion
Y_i	Mass Fraction of Species
N	Total Number of Phases
R	Rate of Reaction
T	Temperature (K)
K	Rate Constant
j	Species
t	Turbulent
r	Reaction
p	Phase
s	Solids
q	Phase