Design and model development of circulating fluidized bed reactor for biomass gasification

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Abstract

Biomass gasification in circulating fluidized bed (CFB) reactor is a research topic that is often discussed lately because CFB technology has the potential for clean gasification and continuous operation. Pyrolysis or gasification is a process where thermal decomposition splits biomass carbon chain into a mixture of fuel gases comprising CO, CO₂, CH₄ and H₂ or so called producer gas or synthesis gas (syngas). During the gasification process, a significant amount of tar is formed that will become a problem when released to the environment. The use of circulating fluidized bed reactor (CFB) is expected to overcome this problem. CFB has high efficiency and can eliminate the tar formation by processing the tar into a separate combustion chamber. This paper will explain the activities regarding the model and design development of circulating fluidized bed of model for biomass gasification systems via computational fluid dynamics simulations. Mathematical models are used to determine the dimensions and configuration of the system, while the simulation is used for the visualization of the results before construction is done. The simulation show that the design parameters developed for the CFB with the capacity of 15 kg/hour biomass results in stable flow condition along the reactor. The pressure contour and velocity topography are constant which give streamline upward flow of material in the reactor that are indicators to good hydrodynamics of the reactor.

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Keywords: biomass gasification; circulating fluidized bed reactor; mathematical models; computational fluid dynamic simulation.

1. Introduction

The production of syngas or producer gas from biomass via thermal decomposition (gasification) is an alternative process in lieu of the complete combustion process that is commonly used in power generation systems. Syngas comprises about 18-20% H₂, 18-20% CO, 2-3% CH₄, 12% CO₂, 2.5% H₂O and the rest, N₂, with the calorific value around 4.7 – 5.0 MJ/Nm³. If the gasification process is conducted with steam as the reacting agent the syngas will have higher quality comprising 50 % CO and 40% H₂, and 10 % other gases such as methane, carbon dioxide and C₂H₆ with the calorific value around 8000 – 9000 kJ/Nm³. The syngas can be used directly as fuel in boilers or diesel generators after cleaning and cooling process. Alternatively, it can be used as input in biofuel production through Fischer Tropsch reaction route. A drawback of gasification process is tar formation. There have been efforts to reduce tar from gas product starting from using downdraft gasifier, fluidized bed gasifier, the use of catalyst and the use of steam. The results vary but basically they show that tar cannot be effectively removed from the syngas stream. Therefore, when designing a gasifier reactor it is important to consider the reactor design, reacting agent, and operational condition. In this work, a parametric study on the design factors, reacting agent, and operational conditions was done to visualize the behavior of the material in the reactor. The dynamic study was conducted using computational fluid dynamic approach whose results become the input to the design tool and setting the operational conditions of the system.

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A review of research results on contemporary thermal gasification technology written by Wang et al. [1], demonstrated the advantages and disadvantages of each reactor as well as the type of reagent used for the gasification process. In addition to the benefits available, it turns out the process of thermal biomass gasification still have challenges in terms of the formation of tar and char excessive and low calorific value syngas if the operating conditions are not in accordance with the characteristics of the processed biomass. Review on modeling of biomass gasification was done by Gomez-Barea et al. [2] showing the flexibility of fluidized bed as a reactor. Other authors [3-13] also show the importance on modeling of fluidized bed reactor as a tool in design and engineering task. The results of those studies show the effect of parameters being studied on the behaviour of the fluid in the reactor.

This paper describes the use of mathematical model and computational fluid simulation to design the reactors. Simulation was done using commercial PHOENICS Computational Fluid Dynamics package. In this paper, the design and modeling of biomass gasification process in a circulating fluidized bed reactor is discussed. The objective is to determine the hydrodynamics of a CFB reactor using visualization technique. Circulating fluidized bed reactor (CFB) reactor was selected because of its better hydrodynamics and efficiency. In CFB, the reaction space is divided into two, namely the gasification chamber and the combustion chamber. CFB reactor works using sand heated by a preheater (LPG burner) which is circulated between the gasification chamber and the combustion chamber. Hot sand serves as an energy carrier to break down biomass molecules into syngas. The thermal decomposition byproducts such as tar pyrolysis will be adhered to the sand. The sand will then be recirculated into the combustion chamber to be burned completely so that the tar attached to the sands becomes inert gases that can be directly discharged into the atmosphere.

2. Background

The selection of the gasification reactor is based on hydrodynamic aspect which is one of the important factors to consider in the modeling and design of the furnace. Fluidized bed system has a better hydrodynamics than that of fixed bed furnace. The hydrodynamics of the fluidized bed system is the effectiveness of the movement and interaction of gases and particles in the reactor chamber [14]. Having regarded the hydrodynamic factors, the optimum operating conditions of the fluidized bed system can be determined. If the fluidized bed reactor is operated not on the specific conditions that are required then its performance will drop. Based on the hydrodynamics, the fluidized bed reactor is classified into several types. Table 1 shows the bed types based on the gas-solids contact process and the gas velocity in the bed, and the ability to maintain a uniform temperature (uniform) during the overall process.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Packed bed</th>
<th>Fluidized bed</th>
<th>Fast bed</th>
<th>Pneumatic transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Stoker fired</td>
<td>Bubbling FB</td>
<td>Circulating FB</td>
<td>Pulverized coal</td>
</tr>
<tr>
<td>Average particle diameter, mm</td>
<td>&lt;300</td>
<td>0.03-3</td>
<td>0.05-0.5</td>
<td>0.02-0.08</td>
</tr>
<tr>
<td>Gas velocity in combustion zone, m/sec</td>
<td>1-3</td>
<td>0.5-2.5</td>
<td>4-6</td>
<td>15-30</td>
</tr>
<tr>
<td>Fluidization velocity relative to terminal velocity, U/U_t</td>
<td>0.01</td>
<td>0.3</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>Gas movement</td>
<td>Upward</td>
<td>Upward Complex, two phase</td>
<td>Upward</td>
<td>Upward</td>
</tr>
<tr>
<td>Gas mixing</td>
<td>Near plug flow</td>
<td></td>
<td>Dispersed plug flow</td>
<td>Near plug flow</td>
</tr>
<tr>
<td>Particle movement</td>
<td>Static</td>
<td>Upward and downward</td>
<td>Mostly upward</td>
<td>Upward</td>
</tr>
<tr>
<td>Particle mixing</td>
<td>Neglected</td>
<td>Almost perfect</td>
<td>Almost perfect</td>
<td>Slightly</td>
</tr>
<tr>
<td>Void</td>
<td>0.4-0.5</td>
<td>0.5-0.85</td>
<td>0.85-0.99</td>
<td>0.98-0.998</td>
</tr>
<tr>
<td>Temperature gradation</td>
<td>Big</td>
<td>Very small</td>
<td>Small</td>
<td>Relatively significant</td>
</tr>
<tr>
<td>Heat transfer coefficient from bed to surface, W/m².K</td>
<td>50-150</td>
<td>200-550</td>
<td>100-200</td>
<td>50-100</td>
</tr>
</tbody>
</table>

Type of reagent and temperature determine the composition of producer gas and thus the calorific value of the syngas. Based on Le Chatelier's principle, the effect of bed temperature which affects the composition of the product depends on the thermodynamics of the reaction conditions. High reaction temperature will improve the formation of a product with an endothermic reaction, but in essence prefer exothermic reaction [15]. The main reactions that occur during gasification with the thermodynamic properties are shown in the following list:
3. Methodology

The research methodology consisted of a laboratory-scale system design approach for simulation and mathematical calculations. The model of circulating fluidized bed reactor (CFB) has a capacity of 15-25 kg of biomass per hour. The reactor is equipped with a forced draft fan to supply atmospheric air into the reactor.

3.1. Design concept

The residence time of the fuel and air mixture in the reactor is an important factor in the design of the system so that the amount of gas formed is maximum while the amount of tar or ‘by product’ is minimum. The reactor is a cylindrical shape with an open top re-burn that has been proven to minimize the formation of tar. Mass and energy balance of the biomass thermal decomposition can be determined from the analysis of the fuel components and products. In general, the volume of gas formed is ranged between 1.5 - 2 Nm³ per kg of fuel. Comparison of the amount of air used is 2.79 percent weight. The optimum conditions of the thermal decomposition reaction will be determined in the design of experiments.

3.2. System design and simulation

System design approach uses mathematical formulation to determine the dimensions of the reactor and other parameters such as the amount of air. Factors that influence the combustion and boiler efficiency calculation can be evaluated through fluid dynamics simulation using PHOENICS software. Simulation will generate visualization of the topography of the combustion in the furnace. Simulations can also be used for optimization of the ratio of air and fuel so that complete combustion can take place that will reduce the number of particles carried in the exhaust gas. Variation of parameters is done to see the topography formed in the flow reactor.

3.2.1 Determination of reactor dimension

In determining the dimensions of the reactor, we use the formulas on fluidized bed which has been developed by other researchers [16]. Parameters that needed to be evaluated are:

- Minimum fluidization velocity
- Particle terminal velocity
- Fluidization velocity during gasification
- Overall reactor height

Fluidization velocity is a function of the density and porosity of the bed of particles. The minimum fluidization velocity required to overcome the pressure loss due to gravity at the moment fluidized bed begins. Loss of pressure is no longer changed when the fluidized bed is formed and past a certain height of the reactor. The minimum fluidization velocity (minimum fluidization velocity), \( U_{mf} \) is determined by the lowest superficial velocity of the gas flowing through the bed. Each \( U_{mf} \) calculated for the sand bed and the bed of biomass (see Equation (1)).

\[
U_{mf} = \frac{dp^2(\rho_p-\rho_f)g}{150 \mu} \times \frac{\varepsilon^3 \Delta \rho^2}{1-\varepsilon}
\]  

where \( U_{mf} \) depends on particle diameter \( d_p \), density \( \rho_p \), porosity \( \varepsilon \) and sphericity \( \phi \), as well as fluidization media in the form of density \( \rho_f \), viscosity \( \mu \) and gravitation \( g \). Fluidization velocity of the gasification process is the ratio between the

\[ \Delta H = 408.8 \text{ kJ/mol} \]

\[ \Delta H = 43.1 \text{ kJ/mol} \]

\[ \Delta H = -172 \text{ kJ/mol} \]

\[ \Delta H = -165 \text{ kJ/mol} \]

\[ \Delta H = -172 \text{ kJ/mol} \]

\[ \Delta H = 206 \text{ kJ/mol} \]

\[ \Delta H = 172 \text{ kJ/mol} \]

\[ \Delta H = 131 \text{ kJ/mol} \]

\[ \Delta H = +100 \text{ kJ/mol} \]
height and the minimum height of the expansion of the fluidized bed (see Equation (2)). Fluidization velocity ($U_f$) during gasification process is the ratio of minimum reactor height ($H$) to the expansion of the bed ($H_f$) as expressed in the following equation (2).

$$\frac{H}{H_f} = 1 + \frac{19.978 \left( \frac{U_f - U_{mf}}{U_{mf}} \right)^{0.738} \rho_p^{0.376} \rho_d^{1.006}}{\frac{0.937 \times 10}{ho_f}}$$

For bubbling fluidized bed, Equation (3) is used.

$$1.2 < \frac{H}{H_f} < 1.4$$

The overall reactor height ($H_t$) is calculated using Equation (4).

$$H_t = TDH + H$$

TDH or threshold disengaging height is a graphical correlation developed by Zens and Weil [5] is depicted in Fig. 1.

![Zen and Weil correlation for TDH calculation](image)

### 3.2.2 Determination of mass and energy balance

The stoichiometric of biomass reaction can be evaluated using ultimate composition of the biomass using Equation (5).

$$C_{\alpha}H_{\beta}O_{\gamma} + \left( \alpha + \frac{\beta - \gamma}{4} \right)O_2 + 3.76N_2 \rightarrow \alpha CO_2 + \left( \frac{\beta}{2} \right)H_2O_{\text{gaseous}} + 3.76 \left( \alpha + \frac{\beta - \gamma}{4} \right)N_2$$

where $\alpha$, $\beta$, and $\gamma$ is the number of carbon atom (C), hydrogen atom (H), and oxygen atom (O) respectively.

For this work, we used rice husk having the following elementary analysis: carbon 36.6 %, hydrogen 5.83 %, nitrogen 3.31 % and oxygen 36.65 %. While the proximate analysis of rice husk is as follows: moisture content 9.3%, fixed carbon 15.4 %, volatile 57.7 % and ash 17.6 %. The syngas composition in the product stream is estimated for having like CO 12 %, $H_2$ 4.0 % and $CH_4$ 3.0%. Hence the stoichiometric reaction of rice husk can be rewritten as Equation (6).

$$x_1(3.05C + 5.83H + 2.29O + 0.24N) + x_2(O_2 + 3.79N_2) + aH_2O + bH_2O \rightarrow x_f(12CO + 4H_2 + 3CH_4 + x_3H_2O + x_4CO_2 + x_5N_2) + x_6C$$

The amount of air, kg, ($m_a$) used for the gasification is given by Equation (7).

$$m_a = 3,600 \cdot (U_f \cdot A \cdot \rho_f) + 0.648 \cdot b$$
where \( A \) is the cross sectional area of the reactor. The stoichiometric coefficient \( (x_2) \) is given by Equation (8). \( M_{w_a} \) is the air molecular weight in kg/kmol.

\[
x_2 = \frac{m_a}{4.76 \cdot M_{w_a}}
\] (8)

The equivalence ratio \( (\xi) \) between air and fuel for gasification is given by Equation (9), where \( (R_{A/C})_r \) and \( (R_{A/C})_s \) are the real and stoichiometric air to fuel ratio respectively.

\[
\xi = \frac{(R_{A/C})_r}{(R_{A/C})_s}
\] (9)

The energy balance for gasification is the difference between the energy obtained from the biomass \( (E_{rh}) \) and air \( (E_a) \) and the energy used for gasification \( (E_g) \) and fluidization \( (E_f) \) given by Equation (10).

\[
E_{rh} + E_a = E_g + E_f
\] (10)

### 4. Results and discussion

The properties of quartz sand and rice husk used in the study are given in Table 1, Table 2, and Table 3.

Table 2. The properties of material used for simulation

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sand</th>
<th>Rice husk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average particle diameter (µm)</td>
<td>385</td>
<td>856</td>
</tr>
<tr>
<td>Density (kg.m(^{-3}))</td>
<td>2,650</td>
<td>389</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.46</td>
<td>0.64</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.78</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Table 3. The design parameters of the reactor

<table>
<thead>
<tr>
<th>1. Gasification Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, m</td>
</tr>
<tr>
<td>Height, m</td>
</tr>
<tr>
<td>2. Combustion Unit</td>
</tr>
<tr>
<td>Diameter, m</td>
</tr>
<tr>
<td>Height, m</td>
</tr>
</tbody>
</table>

Table 4. Operating parameters used in the study

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluidization velocity, m/s</td>
<td>0.7</td>
</tr>
<tr>
<td>Minimum fluidization velocity, m/s</td>
<td>0.07</td>
</tr>
<tr>
<td>Number of nozzle</td>
<td>4</td>
</tr>
<tr>
<td>Nozzle diameter, mm</td>
<td>2.38</td>
</tr>
<tr>
<td>Pressure loss in bed, kPa</td>
<td>6.05</td>
</tr>
<tr>
<td>Height of sand bed, m</td>
<td>0.4</td>
</tr>
<tr>
<td>Rice husk flowrate, kg/hour</td>
<td>Max 25</td>
</tr>
</tbody>
</table>

Design parameters were simulated using computational fluid dynamics program PHOENICS. The simulation results show that the parameters can be used to obtain desired flow in the reactor. The configuration of the furnace uses polar grid as shown in Fig. 2 below. Fig. 3 shows the pressure contour in the reactor. The pressure is high at the bottom of the reactor and decreases as the reactor height increases. This is in agreement with the possible pressure loss along the reactor. However, the pressure loss does not affect the flow of the material since the velocity contour is relatively constant as the reactor height increases (Fig. 4). The streamline chart (Fig. 5) shows the effective interaction of material in the reactor showing a good
hydrodynamics of the system. Based on the simulation results, engineering design was done resulting in a mechanical scheme shown in Fig. 6.

Fig. 2. Configuration and grid of the gasification reactor in PHOENICS

Fig. 3. Pressure contour in the reactor

Fig. 4. Velocity vector in the reactor
Fig. 5. Streamline material flow in the reactor

Fig. 6. Mechanical scheme of reactor design with the capacity of 15-25 kg/hour
5. Conclusions and recommendations

The methodology used in the development of biomass gasification systems using visual simulation of CFB reactor showed stable flow configuration indicating good hydrodynamics. Parameter variation does not significantly affect the topography of the flow of particles in the reactor. Visual representation of the simulation results show the effectiveness of the mixing of air and fuel in the furnace, the effectiveness of combustion, fuel distribution, and the distribution of particles and exhaust gases. The future work is the verification of the modeling and simulation results to be done using experimental data.

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