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Palm empty fruit bunch gasifier characterization using Eulerian-Lagrangian CFD modelling

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Abstract. Energy efficiency is crucial for many developing countries, including Indonesia. One of the solutions is to shift fossil fuels to an alternative source of energy, like biomass which is also available abundantly. Biomass conversion technique like gasification using palm empty fruit bunch is essential considering its potential in Indonesia. Advanced technology with a cost-effective and highly efficient gasification process is required to promote this method, especially in a rural area. Computational analysis for design and initial study is mandatory because gasification involves complicated chemical reactions. Biomass gasification characteristic was investigated using Computational Fluid Dynamic (CFD) program STAR CCM+. The Eulerian-Lagrangian concept was employed to model the gaseous phase (air) and solid phase (biomass particles) of biomass gasifier accordingly. Each of the gasification syngas formation - i.e., CO, N2, CH4, and H2 respectively - were analyzed. The objective of this paper is to characterize biomass gasification steps started with drying, thermal decomposition/pyrolysis, partial combustion of gases, vapor, and char, and finished with the gasification of decomposed products.

1. Introduction

Global energy demand accelerates along with the expansion of the world's economy, in 2009 about 12 billion tons of oil equivalent consumed worldwide and projected to increase by 50% by 2035 [1]. Therefore, energy supply and demand has been more and more crucial in international trade. On the other hand, carbon emission from fossil fuels is also anticipated to grow significantly, which will directly connect with climate change. The quest for renewable and environmentally friendly energy like wind, solar, hydro, and biomass had been developed intensively to answer the challenge [2].

Compared to other renewable resources, biomass possesses benefit because of its available immensely over the world [3]. After coal, petroleum and natural gas, biomass is the most important source of energy with about 10% of the total energy in the world. Along with Malaysia as the most prominent Crude Palm Oil (CPO) in the world, Indonesia is leading in the market with more than 20 million metric tons and 10 million hectares. CPO is made from oil palm tree (*Elaeis guineensis*) and produces a significant amount of biomass. About 4 kg of dry biomass produced for every 1 kg of CPO, most of them derived from oil palm empty fruit bunch and oil palm trunks [4].

Biomass naturally has a low energy density, and its bulky size makes an issue in handling, storing and transportation. Biomass needs to be converted into another form of energy. Biomass gasification seems to be a more promising technique than another conversion because of its non-oxidation condition and relatively low emission. Syngas produced could be used as fuel in an internal combustion engine, gas turbine to produce heat or power, also for feedstock in the synthesis of liquid fuels and another chemical.

Drying as the first step of gasification is necessary to eliminate moisture from the biomass. Upon entering the gasifier, biomass gains heat from the hot zone and perform the drying, thus release water from it. At a temperature higher than 100 ^{o}C, the loosely bound between water and biomass is removed irreversibly. As the temperature increase to around 200 ^{o}C, the low molecular weight volatile matter in biomass start evaporating. Pyrolysis is the second step after drying; it is the thermal crackdown of larger hydrocarbon molecules into smaller biomass molecules without chemical reaction with air or another gasification medium. Next stage is the partial combustion that has several possible paths: Gases that consist of CO, H_2, CH_4, and H_2O; or liquids in the form of tar, oil, and naphtha; and oxygenated compounds like phenols and acid, and solid-state represented by char. The last process is the char gasification and is considered the most critical reaction following the previous process [5].

Numerical analysis of gasification using commercial software STAR CCM+ version 9.02.007 was performed in this paper. At present, discussion about CFD analysis of biomass using palm empty fruit bunch is insufficient. Only a limited number of reported works on CFD modeling of palm empty fruit bunch gasification to our knowledge. For example, thermal flow and gasification of coal gasifier using applied computational model CFD. The multiphase flow was modeled with the Eulerian-Lagrangian concept, the gaseous phase was performed by the Eulerian approach, while the solid coal particle phase was performed by the Lagrangian approach [6].

2. Methodology

The meshed geometry used in this paper is presented in figure 1. The gasifier has 1350 mm in height and 290 mm in diameter based on gasifier dimension calculation [7]. There are opening for air inlet, biomass inlet, and syngas outlet. The biomass used in the simulation was palm empty fruit bunch with the proximate and ultimate analysis is given in table 1 [8]. Three meshing types used in this paper are (a) surface mesh to mesh the primary surface to specify discretized mesh appropriate for the CFD, (b) polyhedral mesh to produce a volume mesh consist of polyhedral shaped mesh and (c) the prism layer mesh to project the interior mesh back to the wall boundaries to construct prismatic shaped mesh. Mesh sensitivity analysis was performed with three different mesh to obtain the optimum meshing size and most efficient calculation time.

Table 1. Ultimate and Proximate Analysis [8]

Element	% (Weight)	Component	% (Weight)
C	61.51	Volatile	77.46
H	10.51	Fixed Carbon	17.25
O	26.00	Ash	5.29
N	1.98		

A wide variety of flow processes involve the transport of dispersed phases like solid particles, liquid droplets, and gas bubbles by continuous phase like gaseous or liquid. In principle, Eulerian-Lagrangian CFD modeling implies that continuous gas phase was solved with transport equation, while the trajectory of discrete particles was tracked with the calculated gas field. Continuous phase and discrete phase interaction were using some governing equations, by considering the exchange of mass, energy, and momentum between two phases.

This paper proposes a Lagrangian approach for biomass particle in solid and dispersed discrete phase and Eulerian method for air as a gasifying agent in gaseous and continuous phase. Governing equations for the dispersed discrete phase are particle motion, the trajectory of particle and temperature of particles. While governing equations for the continuous phase are conservation of mass (continuity equation), conservation of momentum (Newton's Second Law), and conservation of energy (1st Law of Thermodynamics). Another equation employed to model the turbulence are turbulent kinetic energy and turbulent dissipation rate, and species transport equation.

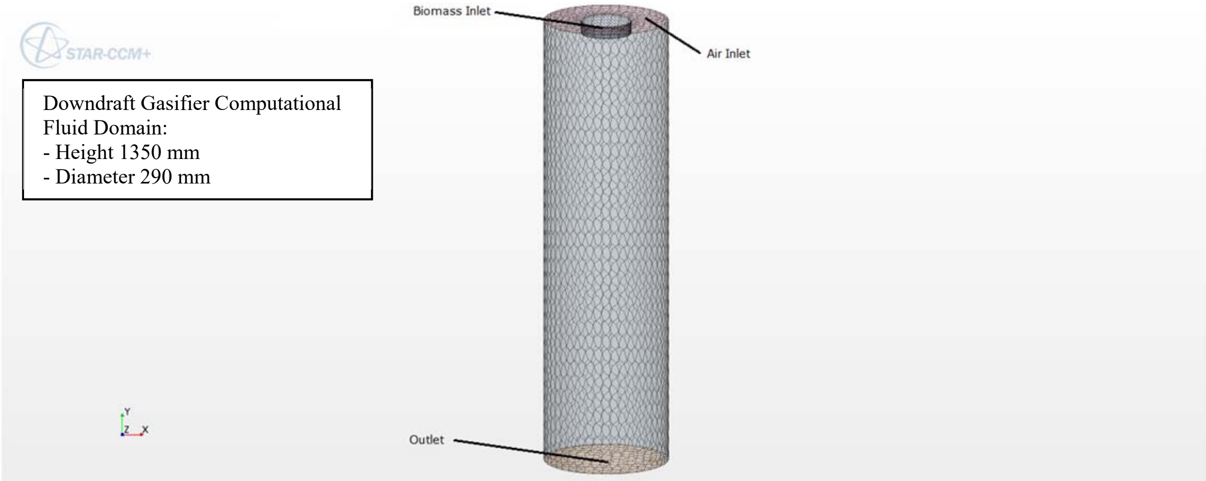

Figure 1. Meshed geometry.

Chemical kinetics equations employed are coal moisture evaporation, raw coal devolatilization, and first-order char oxidation. In coal moisture evaporation model, biomass particles are assumed to be coated by moisture particles, and moisture evaporation happened immediately just before the mass transfer process occurred. Raw coal devolatilization is defined as a process when the volatile matter is removed from the biomass particle. First order char oxidation considers remaining coal left after devolatilization. Char will be reacted with oxygen, water, and carbon dioxide to generate products [6]. Biomass char oxidations associated with several reactions between char and the gasification medium like oxygen, carbon dioxide, and steam are as follows:

$$\text{Char} + O_2 \rightarrow CO_2 + CO \quad (1)$$
$$\text{Char} + CO_2 \rightarrow CO \quad (2)$$
$$\text{Char} + H_2O \rightarrow CH_4 + CO \quad (3)$$
$$\text{Char} + H_2 \rightarrow CH_4 \quad (4)$$

Equations (1) to (4) demonstrate corresponding biomass gasification medium (oxygen, carbon dioxide, and steam) reaction with solid biomass and transform it into lower molecular weight gases such as carbon monoxide and hydrogen. All the above equations are heterogeneous because they involve different phase. Two homogeneous reactions were carried out in the biomass combustion model as follows:

$$\text{Biomass Volatile} + aO_2 \rightarrow CO + bH_2O + cN_2 \quad (5)$$
$$CO + H_2O \rightarrow CO_2 + H_2 \quad (6)$$

Biomass Volatile described by $CH_xO_yN_z$ in the dry ash free condition subjected to devolatilization. In STAR CCM+, Biomass Volatile was represented as CoalVolatile component, where value x, y, and z were obtained from the biomass ultimate and proximate analysis on table 1 [8]

3. Results and discussion

All biomass gasification steps (drying, thermal decomposition/pyrolysis, partial combustion and gasification of decomposed products) has been performed in this model. Biomass volatile matter has been released, and the mass fraction of the syngas product consists of N_2, CO, CH_4, and H_2 were analyzed. Heterogeneous reactions (1) – (4) occurred between char and O_2, CO_2, H_2O and H_2 as oxidizing agents resulting production of gaseous species. Homogeneous reaction (5) – (6) take place to generate CO, H_2O, N_2, CO_2, and H_2.

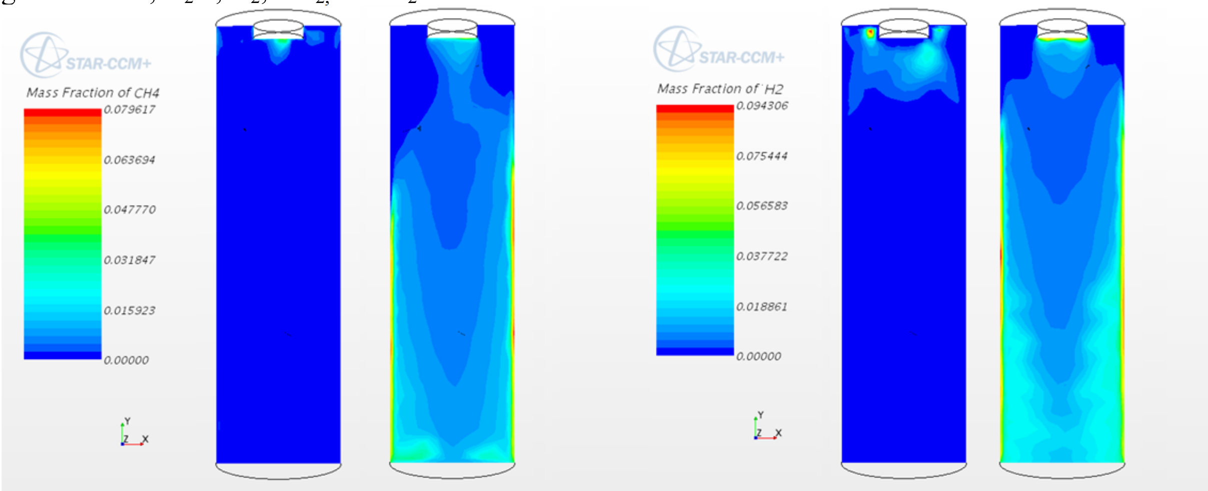

Figure 2. Mass fraction formation of CH_4 and H_2.

Formation of CH_4 could be seen in Figure 2. During early formation, the devolatilization process happened and discharged an extensive amount of volatile matter. The volatile matter then disintegrates into CH_4 and CO. As a result; there will be a more significant amount of CH_4 during this stage. As the process continued, CH_4 will be reacted with H_2O to generate CO and H_2. Therefore, in the final stage, the concentration of CH_4 will be decreased. H_2 was formed because of char oxidation, and homogeneous reaction occurred in the initial stage. As the gasification continued, H_2 will be reacted with O_2 and H_2O will be formed. H_2 consumption will lead to decreasing concentration on the later stage.

During the gasification process, there is the constant production of CO because of heterogeneous and homogeneous reactions. During the original composition, the char oxidation reaction occurred that will produce CO as a product, so in this stage, CO concentration was higher. As the gasification process continued, homogeneous and homogeneous reaction happened and generated more CO. Therefore, the concentration of CO will continue to increase because of this phenomenon as shown in figure 3. Air that consist of O_2 and N_2 enters the gasifier from the top of the gasifier. Hence, the concentration of N_2 is higher compared to the bottom as most N_2 reacted with a hydrocarbon to form tar.

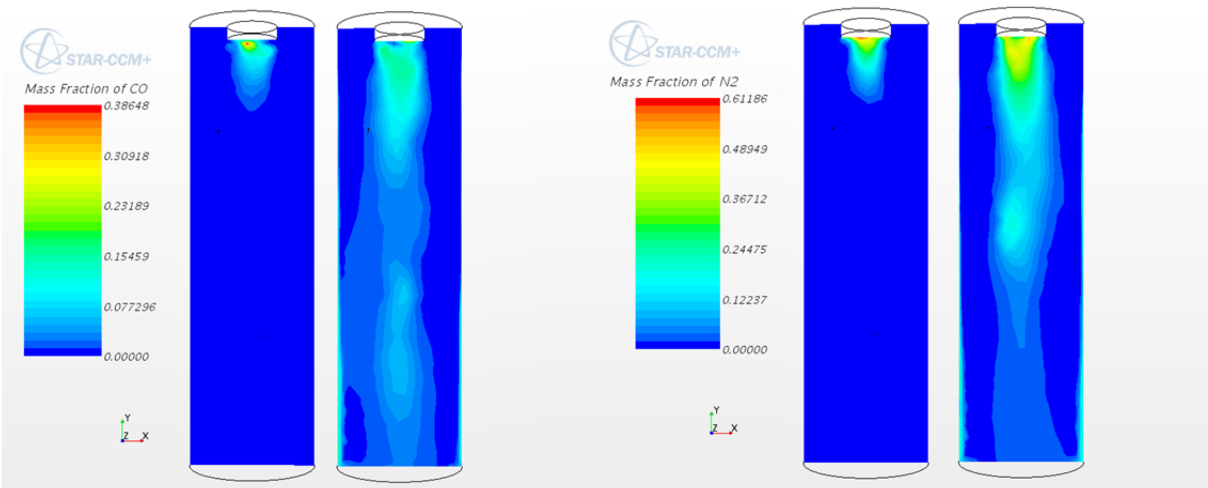

Figure 3. Mass fraction formation of CO and N_2.

Air enters the gasifier at an initial temperature of 25 °C, and temperature increases continuously as the exothermic reaction occurred. Shortly after devolatilization takes place, there will be homogeneous (5) – (6) and heterogeneous reactions (1) – (4) which are endothermic reactions. As a result, the temperature will be slightly decreasing after devolatilization. Figure 4 shows the temperature distribution along the axis of the gasifier and the contour of temperature within the gasifier. The higher temperature detected in an area where biomass contact with air. In this area, there is plenty of fresh air and unreacted biomass that will initiate exothermic devolatilization reactions. Therefore, increasing temperature could be seen at the higher part of the gasifier. Endothermic reactions occurred when we move to the lower part of the gasifier which will decrease the temperature within the gasifier. Modeling result shows compliance with references [6].

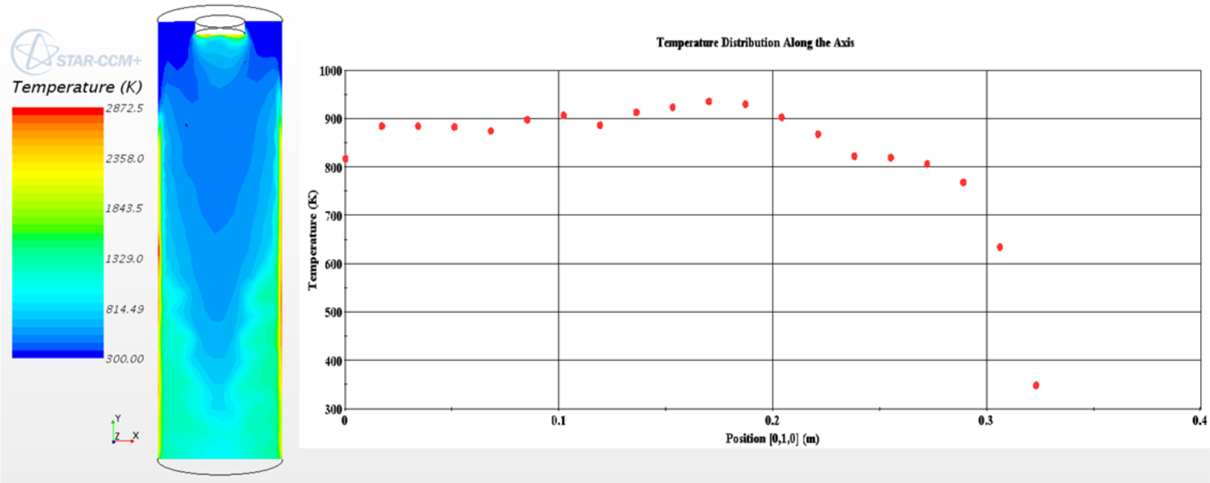

Figure 4. Temperature distribution.

4. Conclusions

Based on the results obtained from this study, the following conclusions could be made: (a) Gasification steps started with drying, followed by devolatilization or thermal decomposition partial combustion of gases, vapor, and char, and finalized with gasification of decomposition products have been successfully carried out with STAR CCM+. (b) The temperature during devolatilization was initially high caused by an exothermic reaction. Along with the end of the endothermic reaction, the temperature was decreasing. (c) Syngas produced by gasification are CO, N_2, CH_4, and H_2, all demonstrate acceptable decency with references. The future experimental investigation should be conducted to validate the modeling analysis.

5. References

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