

A Comparative Numerical, Analytical and Experimental Analysis of Downdraft Gasification Performance for Palm Empty Fruit Bunch

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Abstract- Gasification is believed to be the most effective and efficient compared to another biomass conversion. However currently no comparative study of biomass gasification that investigates all three means of solving engineering problem: a numerical, analytical and experimental analysis. Particularly for palm empty fruit bunch even though it is potentially available in Indonesia. In this comparative study, numerical analysis using Eulerian-Lagrangian Computational Fluid Dynamics (CFD) modeling was chosen and correlated with available experimental data published earlier. An analytical method using a zero-dimensional model or thermodynamic equilibrium model was selected to show the maximum possible gasification performance. Comparative assessments were made of different problem-solving methods to understand the most suitable techniques that will be a benefit for researchers and users.

Keywords- Gasification; Numerical; Analytical; Experimental Analysis

I. INTRODUCTION

The energy crisis has become a worldwide issue since fossil fuel deficiency and growing interest in climate change caused by greenhouse gas emissions that will lead to global warming. Extensive consideration has been concentrated at the development of an alternative source of energy. Several requirements should be fulfilled for alternative energy, such as technically feasible, cost-efficient, environmentally friendly, plentifully available and possess sustainable aspect.

Some alternative source of energy is currently available, like solar, geothermal, wind, hydro and biomass. Among the other alternative source of energy, biomass has been given prominence for its advantages like available abundantly and harmless to the environment because of carbon-neutral character.

Indonesia and Malaysia are two leading crude palm oil (CPO) producers in the world that deal with more than 90% of total global production. CPO production in Indonesia is estimated at more than 20 million metric tons and covering 10 million hectares. An oil palm tree produces a significant amount of biomass, about four kg of biomass wasted for each kg of CPO produced. Most of the biomass is coming from oil palm empty fruit bunch, and the remaining are fronds and trunks [1].

Biomass should be converted into another form because of its bulkiness and inconvenient form cause issue on the storing, and transportation. Gasification is the thermochemical process that converts carbonaceous material like coal or biomass into valuable gaseous fuel or chemical substance. Compared to another biomass conversion, gasification is thought to be one of the most productive and potential techniques of excerpting energy entrenched in biomass and is considered the most excellent possible choice for reusing solid waste material [2].

Biomass gasification incorporates a complicated series of chemical reactions. The first phase is drying the biomass to take the moisture content out of the biomass; this process happened within a temperature ranging from 300 °C to 400 °C. The second step is the pyrolysis or thermal decomposition, usually occurred within 500 °C to 600 °C. The third step is the partial combustion of gases, vapor, and char. An exothermic reaction occurred which release the heat. The last stage is the gasification of decomposition products; this mechanism takes place in the absence of oxygen and considers as endothermic reactions.

Because of its complexity in operation and time needed in installment, it is hard to investigate numerous working conditions of biomass gasifiers. Some researchers have anticipated the performance of gasifiers through mathematical modeling calculation. Equilibrium approach for the gasification reactions with considering any possible discrepancies from equilibrium and improve the equilibrium model to validate experimental results has been carried out. Heat balance calculation was employed to express an outcome of gasifier performance, and a comparative study was made with the available literature results and experimental outcome [3]. Downdraft gasifier performance prediction utilizing equilibrium-based modeling has been performed. The result showed that increasing moisture content in biomass material and increasing the temperature of gasification will decrease the calorific value of the syngas produced [4]. Stoichiometry equilibrium models to enable the analysis of gasification parameter effect to the gasification process for specific biomass source has been established. Four models were examined to discover the syngas composition. Models are based on the theoretical equilibrium constants and were modified with some correction factors using available experimental results [5].

There are three methods for solving engineering problems: numerical that based on approximate solutions to differential equations mathematical model, analytical that based on the direct integration of differential equations of mathematical models, and experimental that based on the experimental measurements of a model or the realistic full-scale object. This paper aims to compare a numerical simulation and present a simplified analytical approach that complements with the experimental investigation for biomass gasification using empty fruit bunch.

II. MATERIALS AND METHODS

A. Analytical Model

Zero-dimensional model is associated with the thermodynamic equilibrium model considering its independent spatial character, and all the chemical reactions were reaching an equilibrium state. There will be slight discrepancies between the zero-dimensional model with the actual process. However, this model is necessary to anticipate the peak achievable gasification performance. Zero-dimension model is also suitable for the development of the optimum operating condition. It could be employed as the initial technical and economic analysis of the gasification process.

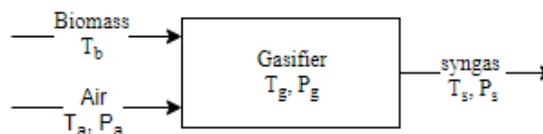


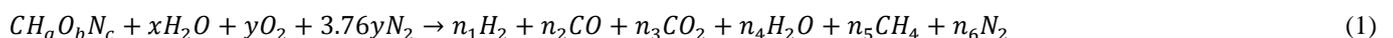
Fig. 1 Gasification Analytical Model

The gasification process studied in this work is illustrated in Fig.1. Input for the gasification model is the biomass derived from palm empty fruit bunch and enters the gasifier at temperature T_b . Air is introduced to the gasifier with the composition of 21% oxygen and 79% nitrogen mass based. Air temperature and pressure are T_a and P_a respectively. The gasifier operates at a temperature of T_g and pressures P_g . The output of the model is the syngas produced with temperature T_s and pressure P_s .

Following assumptions employed in this model are as follow [6].

- All chemical reactions in the models occur in thermodynamic equilibrium. The concentration of species and temperatures are equal all over the gasifier because of space independent conditions.
- The raw biomass derived from empty fruit bunch already in the dry ash free state and the compound formula is $CH_aO_bN_c$. The values of a, b and c are established from the biomass proximate and ultimate analysis data shown in table 1.
- an adiabatic process takes place during the process, all reactions happened without transfer of heat nor transfer of mass between the system in gasifier and environment, as a result of complete isolation in the chamber.
- steady-state condition already reached in the system, meaning that no change in energy and mass of the system under consideration concerning time.
- All of the biomass is transformed into syngas species consist of N_2 , H_2 , CO , CO_2 , and CH_4 . No remaining solid carbon left after the gasification process. The ideal gas law is applied to all of the gases

Global biomass gasification reaction using air as gasification agent could be written as equation (1) below



Where a, b, and c are hydrogen, oxygen, and nitrogen number of atoms, and could be derived from the ultimate and proximate analysis shown in table 1.

TABLE 1 EFB ULTIMATE AND PROXIMATE ANALYSIS [7]

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

Required information needed for the input of the model is as follow

- Biomass chemical composition utilizing date from ultimate and proximate analysis
- Biomass and air Initial temperature derived from the ambient temperature

- Equilibrium temperature ranged from 800 to 1000 °C
- Equilibrium constants used in gasification reactions (methane forming and water gas shift reaction)
- Thermodynamic data for the chemical substance involved in reactions, such as enthalpy for formation (H_f°) and specific heat (C_p) taken from reference [8].

Expected output from the model is syngas compositions as the final gas released once the equilibrium reached, and the heating value determined from the composition of CO, H₂, and CH₄ heating value.

B. Numerical Model

A numerical model was done with 3-dimensional steady state process to model gasification based on the K- ϵ turbulence model. The Eulerian and Lagrangian model was employed to calculate the dynamics of biomass particles according to the coal combustion model in Star CCM+ version 9.02.007. The coal combustion model with Lagrangian particles was selected for simulating suspension firing of biomass. The model consists of three heterogeneous reactions shown in equations (2), (3) and (4)

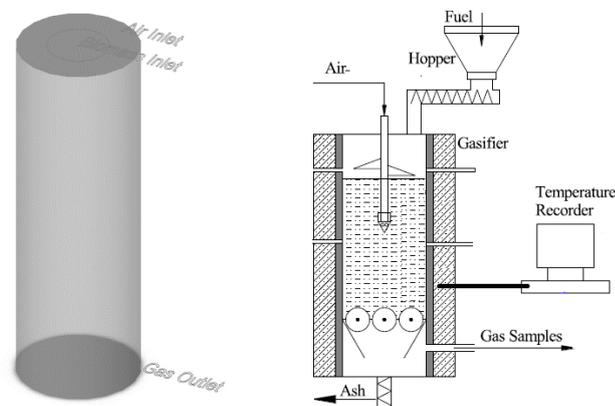


Fig. 2 a. Gasification Numerical Model and b. Gasification Experimental Model

Biomass without ash was subjected to devolatilization and appear in the volatile matter described as $\text{CH}_a\text{O}_b\text{N}_c$. In Star CCM+ the biomass volatile was modeled as CoalVolatile substance, while a, b, and c are the number of an atom and calculated from biomass ultimate and proximate analysis shown in table 1. Another three homogeneous reactions are carried out in the model as follow:



The dimension of the gasifier is a cylinder with 0.4 m diameter and 1.0 m in height (Fig.2 a) and considered as a computational fluid domain. The operating conditions are using 1.0 kg/s biomass flow rate and 0.4 kg/s air flow rate.

Physics simulation chosen for the numerical model is particle type for performing momentum balance for material particles. While multi-component coal was selected for material calculation, and coal combustion was used for mass transfer simulation. The energy model for Lagrangian particles is performing heat transfer coefficient, and RANS model employed to simulate the turbulence dispersion in the Lagrangian particle tracks. Two-way coupling between the continuous phase and Lagrangian particles was preferred because the size of Lagrangian particles are relatively higher compared to the continuum volume cells. The coal moisture evaporation performed the coal combustion model with first order char oxidation and two-step devolatilization model [9].

C. Experimental Model

The numerical and analytical model was characterized by the available experimental results as in [10] and [11] The gasifier tested was the fixed bed, downdraft open top type. The gasifier was designed and assembled at laboratory scale to maintain a

simple operation and could be rerun easily. The geometrical specification is available in Fig.2 b. The gasifier was made from refractory cement surrounded by a stainless-steel tube to bear the high temperature during the gasification [10] and [11].

Air is introduced, controlled and measured by flow meter that was coupled with compressed air supply. Syngas conditioning was performed to measure the syngas compositions (H_2 , CO , CH_4 , CO_2 , N_2) with a gas chromatograph. Once gasifier was loaded with biomass, the fire was ignited, and the air was filled at the same time. Gasification process was taken place from top to bottom.

During the process, the temperature was measured with some thermocouples (T_1 - T_8) to obtain the temperature profile within the gasifier. Data acquisition program was performed with Lab view the software, so the storage and real-time visualization could be achieved. Temperature are monitored every 60 seconds with type K thermocouples located at 0.06, 0.13, 0.20, 0.27, 0.34, 0.41, 0.48, and 0.55 m above the grate at the bottom. The thermocouples could be adjusted to measure the radial temperature difference. The temperature will be shown as average temperature.

Syngas produced from the gasifier was collected after steady state condition have been reached. The original gas composition was analyzed with a gas chromatograph. Five-time repetition was conducted to ensure the reliability of the result analysis.

The objective of the experimental model was to analyze the syngas composition and heating value produced by gasifier. The experimental data acquired will establish a precise and convenient tool to validate the results from the numerical and analytical model.

III. RESULTS AND DISCUSSION

Syngas and Heating Value (HV) obtained from the numerical and analytical model was validated with some available experimental results utilizing Root Mean Square Error (RMSE) as follow.

$$RMSE = \sqrt{\frac{\sum_i^N (exp_i - model_i)^2}{N}} \quad (8)$$

Comparative analysis was carried out by contrasting results from the suggested model (N and A) with numerical reference (N_1), analytical reference (A_1) and experimental model (E).

The experimental model (E) was utilized to validate the model in this paper. Based on the comparison in table 1, it was found that the model suggested in this work is mainly consistent with the experimental model. Suggested models are better because they have smaller RMSE compared to other models.

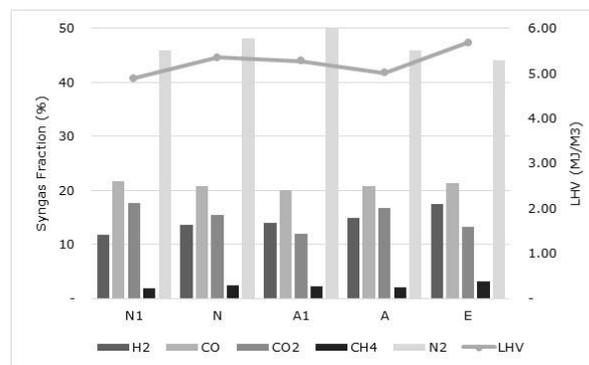


Fig. 3 Syngas Composition and LHV

Some discrepancies for the less fraction of H_2 , CO , CO_2 and more fraction of CH_4 and N_2 are caused by assumptions in developing the models like entirely equilibrium and no residue after the gasification process. Comparison between numerical (N) and experimental (E) of the temperature distribution inside the gasifier is shown in Fig.4 below.

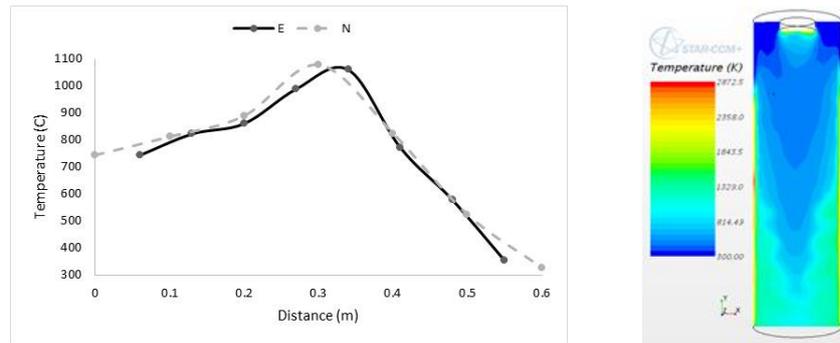


Fig. 4 a. Temperature Axial Profile and b. Temperature Distribution

Biomass was stuffed into the gasifier and was ignited from the top. Hence the biomass material was subject to drying, thermal decomposition (pyrolysis), partial combustion of gases vapor and char, and gasification of decomposition products.

The drying step takes place on the top of the gasifier with temperature ranging from 300-400 °C.

The distance above 0.4 m from the bottom of the gasifier is the pyrolysis area with a temperature below 600 °C. The biomass material was decomposed into some volatile like CO, CO₂, H₂, and CH₄. The gas from this reaction will be moved downwards. Beneath the pyrolysis area is the partial combustion of gases, vapor, and char. In this area, char and volatile gas were oxidized with homogeneous air as gasification agent — a large amount of heat released from this process and is required for the whole gasification process. The temperature in this area reaches 1000 °C as seen in Fig.4 a.

TABLE 2 SYNGAS COMPOSITION AND LHV COMPARISON

	NI	N	A1	A	E
H ₂ (%)	11.87	13.71	14.00	14.95	17.50
CO (%)	21.78	20.77	20.14	20.85	21.30
CH ₄ (%)	17.73	15.54	12.06	16.85	13.30
CO ₂ (%)	1.97	2.47	2.31	2.01	3.10
N ₂ (%)	45.98	48.11	50.79	45.91	44.20
LHV (MJ/m ³)	4.98	5.36	5.28	5.01	5.69
RMSE	3.35	2.66	3.44	2.16	-

The gasification of decomposition products occurred on the last bottom part of gasification. The oxygen is almost used up, and only ash and unconverted carbon are remaining. As a result of some endothermic reactions, temperature decreases into 800-900 °C.

Temperature distribution within the gasifier is illustrated in Fig.4 b. Air was initially introduced into the gasifier at 25 °C (298.15 K), as the reactions advanced, hot air react with biomass particles and an exothermic reaction occurred. Temperature increase continuously, as a result of these reactions. Endothermic reactions take place in the gasification of decomposition products. Hence there was a temperature decrease in this zone.

From the top of the gasifier, the drying process takes place along with the lighter devolatilization components. Pyrolysis gases and char were generated and moving downwards — oxidation process the pyrolysis gases and release heat. Heat generated was used for biomass drying and devolatilization in the area above. The syngas produced from the reduction zone were collected for analysis.

It could be noticed that good agreement presents between the numerical and experimental temperature profile results. Hence the numerical model anticipates the gasifier temperature reasonably well.

IV. CONCLUSIONS

The present study compares the numerical, analytical and experimental analysis in the area of biomass gasification with palm empty fruit bunch as a biomass source. The information above will be beneficial for researchers and planners by acting as guides for designing and applying an appropriate gasifier for the intended application.

A zero-dimensional thermodynamic equilibrium model was found to be practical in anticipating the performance of biomass gasifier. It could be characterized that either pyrolysis and gasification are enforced through the oxidation zone with the highest

temperature. The equilibrium process occurred even in a relatively short period. An analytical model is simple but also have some restraints; it is suggested that a modified equilibrium model with empirical characteristics could develop the accuracy of the models.

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