Numerical Study of Multistage Municipal Solid Wate Gasification Downdraft System With Air Ratio Pyrolysis, Oxidation, and Reduction 1:8:1

Rizqiana Yogi Cahyaningtyas[1*], Bambang Sudarmanta[1] and Arif RahmanSaleh[1]
[1]*Department of Mechanical Engineering, ITS, Sukolilo Surabaya 60111, Indonesia*

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Abstract: This research was carried out numerically to determine the sequential process in each zone due to pyrolysis, oxidation, and reduction air input ratios of 1: 8: 1. Whereas equivalent ratio (ER) is fixed at 0.4. The simulation on the reactor is carried out completely and separately for each zone, by applying the reaction according to the zone. Computational Fluid Dynamics (CFD) software is used to predict syngas composition, chemical reactions, and temperature distribution in each zone. The making of geometry, meshing, and determination of the modeling domain is done with Gambit 2.4.6 software. While numerical simulations are performed with Ansys Fluent 15.0 software. The modeling used is the standard model k-epsilon, Radiation P1, the transport species model with turbulence used is finite-rate/eddy-dissipation, and Discrete Phase Model (DPM). So different chemical reactions are considered in the reactor depending on the operating zone, oxidation and reduction. A three-dimensional modelling for the geometry is used. For the purpose of model validation, experimental data of temperature profiles and syngas composition are used. Besides, the influence of concentration of an oxidant agent is numerically investigated. Results show that the maximum temperatures reached in oxidation and reduction processes are, respectively, 932.38°C.

1 INTRODUCTION

Gasification is a thermochemical process that converts carbon materials such as biomass into useful gas fuels or becomes chemical raw materials through a partial oxidation process with air, oxygen, or steam(Basu, 2013). The performance of the gasification process can be reviewed based on gas quality, namely gas composition, LHV gas, cold gas efficiency, and tar content. Gasification is a chemical reaction that is very sensitive to temperature changes and air supply. Increasing the gasification temperature can be done by modifying a single downdraft type air reactor (oxidation zone) to double / multilevel air input. The gasification process is influenced by biomass characteristics, gasifier design, gasifying agent, and air-fuel ratio (AFR) ratio. Knowing the effect of adding air to the pyrolysis zone and the reduction zone on gasification performance can be done by experiment. The research and experiment process certainly require time, huge costs, and repeated experiments to get the desired results. So modeling can be an alternative.

Dzulfansyah (2014) analyzed the performance of downdraft type rice husk gasification reactors for several simulation scenarios of 70°, 80°, and 90°throat angles, as well as 10°and 20°nozzle angles. In the simulation, the k-epsilon model is used as a viscous model (turbulence), the reactions involved in the gasification process (3 heterogeneous reactions and 6 homogeneous reactions) are solved by the finite rate / Eddy dissipation model. Comparison with the test data results in a RMSE value of 0.78%. The simulation is capable of predicting the composition of the gas quite accurately but is unable to accurately predict the temperature accurately in part of the reactor zone (drying and pyrolysis). In addition, the temperature distribution is not evenly distributed, there is no reaction as a result of air input. Hidayatulloh (2018) carried out modeling of the gasification process in the reactor with the inlet air temperature variations of the oxidation zone, namely 80°C, 110°C, 150°C, 180°C, and 200°C. The model used is the standard k-epsilon model, radiation P1, the transport species model with turbulence used is finite-rate / eddy-dissipation, and Discrete Phase Model (DPM). The results of this gasification study were obtained by increasing the highest

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temperature at the addition of air temperature 200°C at 1004°C in the oxidation zone (924°C experimentally).

2 BACKGROUND

2.1 Basic Gasification Theory

Biomass is a mixture of complex organic matter, such as carbohydrates, fats, and proteins, which includes a small amount of minerals, such as sodium, phosphorus, and iron (Basu, 2013). The characteristics of biomass can be known by doing several analyzes, namely ultimate and proximate analysis, density analysis, humidity analysis, and heat value analysis. The proximate and ultimate MSW test results are shown in Table 1.

The gasification process occurs in four stages, namely drying (T ¡150°C), pyrolysis / devolatilization (150°C ¡T ¡700°C), reduction (800 ¡T ¡1000°C), and oxidation (700°C ¡T ¡1500°C). The gasification process consists of a flammable gas, H_2, CO, CO_2; non-flammable gas, namely N_2 and CH_4, as well as other compounds, such as sulfur, alkali and tar. Product gas quality can be viewed from several aspects, namely gas composition, LHV gas, cold gas efficiency, and tar content. The composition of gas CO, H_2, CH_4 is seen from the results of testing using Gas Crematography. The LHV value is calculated by:

$$LHV_{syngas} = \sum_{i=1}^{n} (Yi \cdot LHVi) \quad (1)$$

Cold Gas Efficiency is the amount of energy that enters as long as potential energy exits. If M_f is the mass of solid fuel processed in the gasifier (kg) to produce M_g mass of product gas with a LHV value from Q_g, then this efficiency can be stated as follows:

$$\eta_{cg} = \frac{LHV_g \cdot M_g}{LHV_f \cdot M_f} \quad (2)$$

Table 1: Proximate and Ultimate Data of MSW

PROXIMAT	*Moisture Content*	% wt	9,82
	Fixed carbon	% wt	9,69
	Volatile matter	% wt	65,78
	Ash	% wt	14,71
	HHV	kJ/kg	13843
ULTIMAT	C	% wt	39,83
	H	% wt	6,7
	O	% wt	38,11
	N	% wt	0,35
	S	% wt	0,14

The tar content is calculated using the following equation:

$$\text{tar content} = \frac{m_{tar}}{\text{syngas volume}} \quad (3)$$

where m_{tar} = mass of tar (kg) and volume of syn gas (m^3)

Based on its fluidization mode, gasifier is divided into 3 types, namely: fixed bed gasifier, fluidized bed gasifier, and entrained flow gasifier. In general, small-scale gasification uses a fixed bed gasifier (Reed et al., 1988). Based on the direction of feedstock and gas flow in the gasifier, fixed bed gasifier can be categorized into three types, namely, updraft, downdraft, and cross draft (Gai and Dong, 2012). In the updraft gasifier, the direction of feedstock flow down while the direction of gas flow up. In the downdraft gasifier, the direction of the gas and feedstock flow are both downward. Whereas in the cross draft gasifier, the direction of gas flow is kept flowing horizontally with feedstock flow down. Downdraft type gasifiers have advantages including, suitable to be applied on a small scale ((Sheth and Babu, 2009; Vyarawalla et al., 1984)), construction and operation are easy, and produce low tar.

Tar is classified into three, namely secondary and tertiary primary tar. Primary tar is formed at pyrolysis temperature. Secondary tar is formed at oxidation temperature (above 500°C) due to oxidants (oxygen, air or steam). Tertiary tar is formed at a reduction temperature (more than 800°C). In gasification with multilevel air input, the addition of air in the pyrolysis zone can increase the temperature in the pyrolysis zone itself (auto-thermal) and subsequent zones so that it is expected to increase the composition of the gas. The composition of gas products obtained in the oxidative pyrolysis process is more because it reacts with O_2 and in the oxidative process of pyrolysis produces N_2. In the composition of tar, pyrolysis usually produces primary tar, whereas in oxidative pyrolysis it has succeeded in reducing primary tar, and only begins the formation of secondary tar.

2.2 Basic Theory of Numerical Model

Ahmed et al. (2012) classify biomass gasification modeling into two broad categories, namely mathematical models and simulation models. Mathematical models include Equilibrium Models, Kinetic Modeling, and ANNs Models, while the simulation models include CFD Models and ASPEN Plus Models. Computational Fluid Dynamics (CFD) involves mass conservation equations, momentum, energy flow, hydrodynamics, and turbulence in the specified area. In general, there are three stages that must be done in CFD simulations according to Tuakia (Tuakia,

2008), namely pre-processing, processing, and post-processing. In the pre-processing stage, geometry, mesh and boundary layer are made. At the processing stage, calculations are done to solve the equations used. The calculation is done based on iteration to close to the convergence criteria, which is set according to user needs. Post processing is done to analyze and interpret the calculations that have been made. The results are presented in the form of x-y graphs, contours (such as temperature, speed, pressure, etc.), speed vectors, streamlined plots, and also animations can be presented with ANSYS Fluent software.

3 NUMERICAL MODEL

Previous modeling was carried out as a whole by applying all chemical reactions to a downdraft gasifier simulation. This causes the sequential process circuit in each zone to be unknown. Therefore, it is necessary to simulate separately for each zone, by applying the appropriate reaction to the zone. The purpose of this study was to determine the temperature distribution and gas composition in the pyrolysis, oxidation, and reduction zones. Yi is the concentration of combustible gas (CO, H2, CH4), LHVi is LHV syn gas compound.

4 RESULT AND DISCUSSION

4.1 Performance of the Oxidation Zone

Geometry and mesh (Figure 1) are made using GAMBIT software version 2.4.6. with 3-D models using hybrid mesh (a combination of structured and unstructured). Meshing in this simulation has 17,698 nodes and 44,491 elements. Maximum quality of Ortho Skew at meshing is 0.79 where this value is still within Ortho Skew's maximum limit of 0.9. The turbulence modeling used is the standard k-ε model, radiation *P*1, the transport species model with the reaction model used is finite-rate / eddy-dissipation, and Discrete Phase Model (DPM). The boundary conditions are based on experimental data obtained during gasification of MSW. The equivalence ratio (ER) used for this particular case corresponded to 0.4. The external wall is modeled as adiabatic; however, a real process has a non-adiabatic condition due to heat losses to the surrounding. Steady state conditions are also assumed.

Figures 2 and 3 shows the CFD simulation of the combustion of MSW proposed in this work. Figure 2

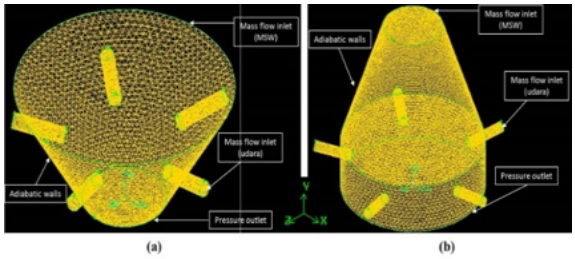

Figure 1: Meshing and Boundary Conditions in the Oxidation Zone (a) and Reduction (b)

Table 2: Kinetic Parameters of Reactions

Zone	Reaction	ΔH
Pirolysis	Volatile → H_2 + CO+CO_2+H_2O+CH_4	
	C+1/2O_2 → CO	-111
Oxidation	CO+0.5 O_2 → CO_2	-284
	CH_4+O_2 ↔ CO_2 +2H_2O	-803
	H_2+0.5× O_2 → H_2O	-242
Reduction	CO+H_2O ↔ CO_2+H_2	-41.2
	CO_2+H_2 → CO + H_2O	
	CO+3H_2 ↔ CH_4+H_2O	206
	CH_4+H_2O ↔ CO +3H_2	+206
	C+CO_2 ↔ 2CO	172
	C+H_20 ↔ CO + H_2	131

Table 3: Kinetic Parameters of Reactions (continue)

Zone	A (kJ/kmol)	E (kJ/kmol)
Pirolysis		
	0.052	6.1× 10^7
Oxidation	2.2× 10^{12}	1.67× 10^8
	4.4× 10^{11}	1.25× 10^8
	6.8× 10^{12}	1.68× 10^8
Reduction	2.75× 10^{10}	6.1× 10^7
	2.2× 10^7	1.9× 10^8
	5.12× 10^{14}	2.73× 10^4
	8× 10^7	2.51× 10^8
	0.00732	1.125× 10^8
	0.00782	1.15× 10^8

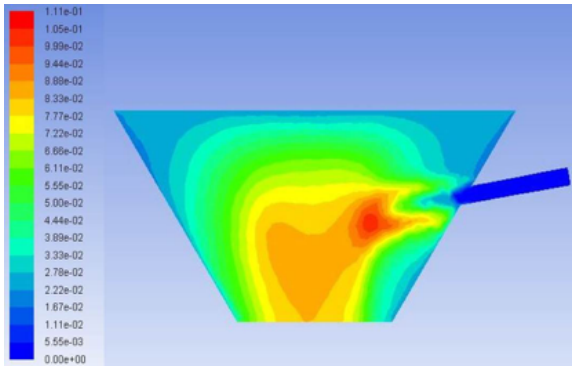

Figure 2: Result for simulation of oxidation zone : temperature profile (°C)

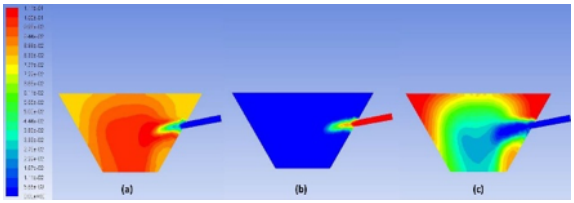

Figure 3: Result for simulation of oxidation zone : contour of mole fraction of CO_2 (a), O_2 (b), CH_4 (c)

depicts the temperature profile, as expected, the maximum is found at the nozzle of the reactor. Such a temperature results because the combustion process is considered as adiabatic. The adiabatic flame temperature is attainable when the reactor contains enough stoichiometric oxygen. It is also observed that the temperature distribution is not symmetrical with respect to the centerline of the reactor.

The simulation also permits to obtain detailed information of each species distribution inside the reactor. Figure 3(a), shows the CO_2 fraction in the reactor. It can be observed that at the center part the CO_2 concentration distribution is higher than that of the outer region (walls). However, it is observed a region with a high quantity of CO_2 located at the upper part of the reactor, where biomass is injected. Fig. 3(b), on the other hand, is the O_2 fraction in the reactor, it shows that at the nozzle of the reactor, the O_2 fraction is higher than that of the other regions of the reactor. As expected, the highest O_2 concentration is observed in the combustion zone where the air is injected. Contrary to the CO_2 concentration distribution, the CH_4 concentration distribution is much higher at the upper part of the gas reactor than that at the lower part (Figure 3(c)).

4.2 Performance of the Reduction Zone

Figure 4 depicts the temperature profile, as expected, the maximum temperature is 932.38°C and is found at at the upper part of the reduction zone, because of the high temperature coming out of the oxidation zone. Such a temperature results because the reduction process also considered as adiabatic.

Figure 5 indicates that the highest CO_2 (a) and CH_4 (c) concentrations are at the top of the reduction zone because these two gases react with high temperature air from the oxidation zone Fig. 5 (b) shows the entrance of oxygen and its fast consumption in the reduction zone just below the nozzle. The sequence of these events causes a stratified formation with high porosity at the top of the reactor. The first event of the thermal analysis corresponds to the moisture release beginning at 400 K, and then in the pyrolysis stage

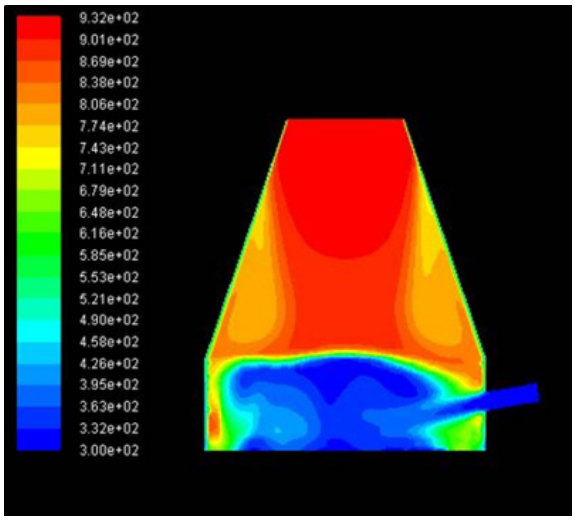

Figure 4: Result for simulation of reduction zone : temperature profile (°C)

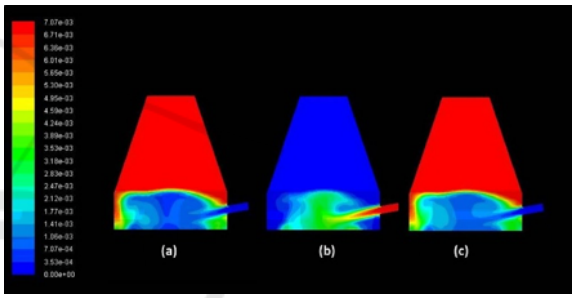

Figure 5: Result for simulation of reduction zone :contour of mole fraction of CO_2 (a), O_2 (b), CH_4 (c)

most of thermal energy is consumed by exothermic reactions occurring in the combustion zone, this takes place at temperatures which range 600–900 K. The third event of the thermal analysis represents the reduction process where a new homogeneous reaction occurs to compose into a low heat value syngas.

5 CONCLUSIONS

In this study, a comprehensive model for a downdraft biomass reactor is developed and applied to the individual simulation of oxidation and reduction processes. The model is able to correctly predict temperature and gas composition. The predicted gas temperature profile is consistent with the experimental data. The effect that the different operating modes of the reactor has on important output variables permits to make suggestions regarding the optimization of the different hermochemical conversion processes.

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