Numerical study of gasification pelletized municipal solid waste using multi-stage air inlet downdraft gasifier

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Abstract. The three-dimensional computational fluid dynamic model is used to simulate the gasification process using a modified downdraft gasifier with two levels of air inlet in the pyrolysis and partial oxidation zone. The aim of this study is to know the influence of air in pyrolysis zone to the gasification performance. Simulation arrangement using k-epsilon for turbulence model, radiation model using P1, kinetic devolatilization model using two competing rates, municipal solid waste pellet fuel is modelled as granular particles and modelled by discrete phase and multiple surface reaction model completed with finite rate/Eddy dissipation. From the simulation results, the maximum syngas composition obtained for CO, H2, CH4, CO2, and H2O was 30.85%, 16.74%, 2.25%, 0.5%, and 0.57%, respectively with LHV 5.325 kJ/kg. Air inlet at pyrolysis zone initiate the pyrolysis reaction under oxidative environment and create a new combustion zone (pyrolysis oxidative zone) with the temperature of 785°C and the partial oxidation temperature reach out 1135°C. The heat energy for the endothermal reaction (drying and pyrolysis) is obtained additional from the heat energy released by the oxidative pyrolysis zone. The modelling results from this study can be used as a reference to improve downdraft gasification performance.

1. Introduction
Increasing human population in 2015 has reached 7 billion people and by 2030 is predicted to reach 8.5 billion inhabitants. Currently, 54% of the world's population lives in urban areas, the proportion is expected to increase to 66% by 2050 [1]. Changes in lifestyle along with the development of the times and technology cause the waste produced every day continues to grow, this is especially happening in big cities. If the waste generated is allowed to accumulate can produce methane gas that can cause negative impact on the environment. In addition, the garbage pile also causes pollution of soil and water due to leachate generated from waste piles. On average, every Indonesian population produces 0.76 kg/day of solid waste. With a population of 261.9 domestic solid waste (municipal solid waste/MSW) generated amounted to 199.044 tons/day spread over an area of 5.193.250 km with a total administrative area of 33 provinces [2, 3, 4].

Solid waste is one kind of waste that can be converted into energy. Before the MSW collected at the landfill, it is necessary to first begin the process of sorting, drying, enumeration, biological process, and energy recovery process. Various methods of converting waste into energy have now been developed such as by harvesting methane gas from the waste, burning waste and biomass to generate energy.
However, the direct waste combustion method leads to negative impacts of harmful emissions and can damage the environment. One method that can reduce waste without producing emissions is gasification [5, 6].

Gasification is one of the thermochemical processes that can convert solids into energy. Gasification consists of several stages starting from drying, pyrolysis, partial oxidation, and reduction. Gasification requires media such as air, oxygen, or water vapor [7]. The gasification process produces a gas called syngas. The gas can be used further for thermal applications or as fuel in an internal combustion engine or chemically reprocessed. Syngas consists of combustible and non-combustible gases, namely CO, H2, CH4, CO2, N2, and tar. Gasification reaction stage occurs inside the gasifier. One of the most commonly used types of the gasifier is a downdraft. This gasifier has advantages over other types (updraft, cross-draft, rotary) because of its high carbon conversion rate, low tar production, simple construction, and reliable technology [7].

Various studies have been done to improve the performance of the gasifier in order to produce high calorific syngas and low tar content. One method used to reduce the number of tars with multi-stage air inlet in partial oxidation zones and pyrolysis zones. A preliminary study was conducted by Sudarmanta [8, 9, 10] which modified single-stage gasifier into multi-stage to know the influence of air inlet and variation of gasification agent. Modifications also performed by Bentzen [11] with adding physical grate on pyrolysis zone to produce syngas with a low tar content of 15 mg/Nm3. Bui’s [12] injects air into the pyrolysis zone resulting in an increase in temperature up to 600°C and produces syngas with a lower tar content than the single stage (from 3600 mg/Nm3 to 92 mg/Nm3).

The air input in the pyrolysis zone can initiate the pyrolysis process in an oxidative environment. When that happens, it will form a new combustion zone above the partial oxidation zone, called oxidative pyrolysis zone. There is a change in nature from endothermal to exothermal (pyrolysis requires 0.28 MJ/kg energy, oxidative pyrolysis releases energy of 7.23 MJ/kg). Char and tar production decreased while the product permanent gas and water vapor increases. There is an increase in temperature in each gasification zone, drying up to 200°C, pyrolysis from 400-725°C, partial oxidation 750-1195°C, and reduction from 950-650°C. Syngas heating value (LHV) reached 7.88 MJ/Nm3 with an efficiency of 89.7% [13, 14, 15].

To know the influence of air inlet in pyrolysis zone on gasifier performance, besides with experimental method is by numerical analysis method. Computational fluid dynamic (CFD) analysis is one of the numerical methods that can be used to predict gasifier performance. Various studies of CFD analyzes have been performed on downdraft gasification. Janajreh [16] undertook numerical studies and experiments on a downdraft gasifier to investigate the temperature distribution within the gasifier. Yan [17] performed a numerical analysis to determine the effect of throat dimension and reduction zone on temperature distribution and syngas composition. Ahmed [18] analyzed the CFD by modeling the four stages of gasification reaction into an asymmetric 3D model to improve the capability of gasifier design based on CFD analysis results. However, none of the previous CFD study for multi-stage gasification analysis. Therefore, the aim of this study is to know the influence of the air inlet to the performance of gasifier in terms of temperature distribution, syngas composition, and low heating value by using CFD analysis.

2. Computational model

2.1. Multi-stage air inlet downdraft gasifier

Gasifier used in this research is downdraft. What distinguishes this gasifier from another is the position of the air inlet as a gasification agent. In the conventional downdraft gasifier, air inlet in the partial oxidation zone whereas in this gasifier the air inlet in the partial oxidation zone and the pyrolysis zone. For numerical simulation, 3D models are used only on the domain of the fluid inside the gasifier. Gasifier model can be seen in Fig. 1. The fuel entering from the surface of the gasifier and at the same time air injected in both zones using 5 nozzles surrounding the gasifier wall. Syngas passes throat and exits through the bottom of the gasifier outlet.
The fuel used is a municipal solid waste in the form of pellets with 60% organic and 40% non-organic composition (6 mm diameter, 15 mm length). The ultimate and proximate analysis is performed to determine the fuel properties and presented in Table 1. Fuel is modelled in the form of granules. The mesh model used is a mixture of tetrahedral and hexahedral due to the complex geometry of each regions. The number of elements used is 164,274. To obtain accurate results of calculations analysis grid independency was performed.

2.2. Simulation model

The simulation was performed using FLUENT 15 (ANSYS.US). The 3-D model is completed in steady-state using energy equations. The turbulence model used is k-ε. Transport equations for species are completed using species transport equation so that a local mass fraction of each species can be obtained. Turbulence-chemistry interactions are solved using a finite-rate/eddy-dissipation model. Fuel particles are assumed to be spherical particle combusting in discrete, secondary phase, which diffuses in the continuous phase and injected on the fuel inlet surface of the gasifier. Devolatilization combusting particle is modelled using two competing rates (Kobayashi model) [19]. The radiation that occurs during the partial combustion process is modelled with the P-1 model. The gravitational force is activated because the syngas is out in the direction of the y-axis. To start the combustion, patch process at the bottom of the nozzle in the 1000 K.

Figure 1. Gasifier model and mesh.

Table 1. Properties of municipal solid waste pellet.

| Analysis  | Contents     | % mass |
|-----------|--------------|--------|
| Proximate | Fixed carbon | 20.19  |
|           | Volatile     | 65.78  |
|           | Moisture     | 9.82   |
|           | Ash          | 4.21   |
|           | Carbon       | 47.265 |
| Ultimate  | Hydrogen     | 6.7    |
|           | Oxygen       | 45.545 |
|           | Nitrogen     | 0.49   |
| Calorific Value (J/kg) | 1.348 x 10^6   |
2.3. Reaction model
The reaction model is arranged according to the sequence of gasification processes of drying, pyrolysis, partial oxidation, and reduction. The drying process is represented by droplet material where the moisture of solid fuel evaporates because its particle temperature lower than its vaporization temperature to be inert heating or vapor (law 1 and 6 thermodynamics) [19].

\[ T_p < T_{vap} \]  

\[ m_p \leq (1 - f_{v,0})m_{p,0} \]  

Once the particles reach temperatures of vaporization temperature, devolatilization process occurs so that the mass of the particles exceed the non-volatile mass of the particles. Devolatilization models used is the Kobayashi model where the devolatilization process is controlled by two kinetic devolatilization rate \( R_1 \) and \( R_2 \) at two different temperatures [19].

\[ R_1 = A_1 e^{-(E_1/R T_p)} \]  

\[ R_2 = A_2 e^{-(E_2/R T_p)} \]  

\[ \frac{m_p(t)}{(1-f_{w,0})m_{p,0} - m_a} = \int_0^t (\alpha_1 R_1 + \alpha_2 R_2) \exp(- \int_0^t (R_1 + R_2) dt) \, dt \]  

Volatile modelling is obtained from the ultimate test result and proximate fuel which yields an equation of chemical formula of volatile C\textsubscript{m}, H\textsubscript{x}, O\textsubscript{y}, N\textsubscript{z}. The volatile decomposes and produces volatile gases of CO, CO\textsubscript{2}, H\textsubscript{2}, H\textsubscript{2}O, CH\textsubscript{4}, and N\textsubscript{2}. This volatile gas can be obtained by performing thermogravimetric tests on the volatile material. It can also be predicted using phenomenological assumptions [16].

\[ C_{0.77} H_{2.6} O_{1.11} N_{0.0137} \rightarrow 0.77 CO + 0.34 H_2O + 0.96 H_2 + 0.00685 N_2 \]  

When the volatile component has fully devolatilated, the surface reaction begins by consuming the combustible fraction \( f_b \) [19].

\[ m_p < (1 - f_{v,0})(1 - f_{w,0})m_{p,0} \]  

\[ m_p > (1 - f_{v,0} - f_{comb})(1 - f_{w,0})m_{p,0} \]  

Surface reaction rate is determined by kinetic and diffusion rate based on kinetic/diffusion-limited theory by Baum and Street [20, 21, 22].

\[ D_0 = C_1 \frac{((T_p + T_{m0})/2)^{0.75}}{d_p} \]  

With kinetic rate :

\[ R = C_2 e^{-(E/R T_p)} \]  

Are weighted to yield a char combustion rate of

\[ \frac{d m_p}{d t} = -A_{p P_{ox}} \frac{D_0 R}{D_0 + R} \]  

Partial combustion of fuel takes place quickly and the average reaction rate is controlled by turbulence mixing. To calculate the chemical reaction between the Arrhenius rate, turbulence mixing rate is used finite-rate/eddy-dissipation model. The reaction in the gasification process consists of two types of reactions: gas or homogeneous phase reaction (gases) and particle surface reaction or heterogeneous (solid-gas) presented in Table 2.
Table 2. kinetic parameter for homogeneous and heterogeneous reactions [23].

| Heterogeneous reactions | Kinetic parameter, A (kg/m²/s/Pa⁰.⁵), E (J/kmol) |
|------------------------|-----------------------------------------------|
| C(s) + 0.5O₂ → CO      | A₁ = 0.052                                    |
|                         | E₁ = 6.1 x 10⁷                                |
| C(s) + CO₂ → 2CO       | A₂ = 0.0732                                   |
|                         | E₂ = 1.125 x 10⁸                              |
| C(s) + H₂O → CO + H₂   | A₃ = 0.0782                                   |
|                         | E₃ = 1.15 x 10⁸                              |
| Homogeneous reactions   |                                               |
| CO + 0.5O₂ → CO₂       | A₄ = 2.239 x 10¹²                             |
|                         | E₄ = 1.674 x 10⁹                             |
| H₂ + 0.5O₂ → H₂O       | A₅ = 6.8 x 10⁸                               |
|                         | E₅ = 1.67 x 10⁸                              |
| CH₄ + 0.5O₂ → CO + 2H₂ | A₆ = 4.4 x 10¹¹                               |
|                         | E₆ = 1.25 x 10⁸                              |
| CO + H₂O ↔ CO₂ + H₂    | A₇ = 2.34 x 10¹⁰                             |
|                         | E₇ = 2.883 x 10⁹                             |
| CH₄ + H₂O → CO + 3H₂   | A₈ = 8.7 x 10⁷                               |
|                         | E₈ = 2.51 x 10⁸                              |

2.4. Simulation process

Two-stage air inlet downdraft gasifier is modelled using the finite volume method [19]. The computation process is done using 3-dimensional gasifier model. Air enters through 10 nozzles divided into two positions, 5 for partial oxidation, 5 for pyrolysis with 10 mm diameter nozzles. Gasifier whole length 600 mm with diameter 165 mm and throat diameter of 63.5 mm. reduction zone starting from throat to gasifier outlet with height 130 mm. The boundary condition of the simulation is taken from the experimental results. Equivalent ratio (ER) for gasification is 0.4 and air ratio between oxidation and pyrolysis 70:30. The boundary condition parameters are presented in Table 3.

Table 3. Boundary condition.

| Boundary condition | value             |
|--------------------|-------------------|
| MSW particle inlet temperature (°C) | 30                |
| MSW flow rate (kg/s) | 0.000397          |
| Air inlet temperature(°C) | 80                |
| Air inlet flow rate stage 1 (kg/s) | 0.000204          |
| Air inlet flow rate stage 2 (kg/s) | 0.0001825         |
| MSW particle density (kg/m³) | 317               |
| MSW HHV (KJ/kg) | 13415             |

3. Result and discussion

3.1. Pressure and flow profile

The pressure profile, velocity and velocity can be seen in Fig. 2. The highest pressure (4.012 bar) occurs at the bottom of the gasifier which is the syngas accumulated and then the pressure is distributed throughout the space within the gasifier. in the upper region of the nozzle to the surface of the gasifier, the pressure is evenly distributed either axially or radially. The lowest pressure (-1 bar) occurring between the above of air nozzle 2 and the top of the gasifier. The pressure difference occurs when the fuel enters the gasifier and starts partial combustion then passes throat and exit the gasifier which can also see from the velocity profile inside the gasifier. The uniform distribution of pressure on the area above the nozzle 2 (Fig. 2) occurs due to the low speed of the gas flow.

The highest gas flow rate (6.7 m/s) begins from throat area because in that area the diameter changes become smaller. The pressure increasing again as the gas passes through the reduction zone and the gasifier outlet. the velocity distribution on the gasifier wall is lower than in the middle because the area is dominated by solid particles while the centre is gas phase. At the air encounter point of any nozzle
accumulation occurs so that the air spreads upward forming a pattern. This accumulation causes oxygen in the area to trigger the combustion. This pattern can be seen from the temperature increase in the area. The pyrolysis reaction does not occur radially, however in the area near the wall.

3.2. Temperature distribution
Temperature distribution does not occur uniformly in the gasifier because of the non-uniform gasifier shape and flow pattern. The highest temperature occurs in the area around the air flow from the nozzle. Because the air is spread and form a pattern on the area of air meeting point, an increase in temperature also occurred in this area. In the gasification process, the temperature is a very important parameter for determining the composition of the produced gas. If the temperature is too low it may cause an imperfect reaction in each gasification zone.

In the throat region until the gasifier outlet, the temperature continues to decrease as heat energy is used for the reduction reaction. The entry of air in the pyrolysis zone lead a shift in the temperature distribution of pyrolysis and drying zones, from the Fig.3 seen there is an increase temperature in the pyrolysis zone near the temperature of the partial oxidation zone, consequently the pyrolysis layer becomes thicker and the drying layer becomes thinner so that the evaporation of the moisture content is faster.

The highest temperature distribution occurs between the air inlet 1 and the air inlet 2. The highest temperature single-stage gasifier occurs only in the region of air inlet 1 [9], the air entry in the pyrolysis zone initiates the oxidative pyrolysis and forms a new combustion zone above the partial oxidation zone. This is indicated by the average temperature of the area of 785°C. In a single stage gasifier, the maximum temperature of that zone is 600°C. Oxidative pyrolysis adequate to generating thermal energy for its above process (drying and pyrolysis) so the heat energy released by the partial oxidation is reduced and the temperature of the oxidation zone achieve 1135°C.
In the area of the air meeting point the temperature is lower than the surrounding area because the amount of oxygen in the area is more than the amount of fuel (lean mixture). This can be seen from the distribution of velocity and oxygen species in the area along the nozzle. In the area along the air flow from the nozzles, the temperature is higher because the amount of oxygen is lower than the amount of fuel (rich mixture).

3.3. Syngas composition and LHV
Syngas composition is one of the important parameters that determine gasifier performance. the resulting gas is divided into two: flammable and non-flammable (CO₂, H₂O, N₂). The calorific value of syngas is calculated based on the percentage of flammable gas (CO, H₂, CH₄). Based on the contour of the Fig.4, the species within the gasifier, on top of the drying process occurs which is marked by the release of moisture content that turns into H₂O gas. after that, the amount decreases in the pyrolysis zone because in this zone the amount of H₂O released is lower. H₂O gases increase again from the partial oxidation zone to the reduction due to oxidation reactions of hydrogen and methane and methanation reactions in the reduction zone.

![Figure 4. Product species distribution (CO, H₂, CH₄, CO₂, and H₂O).](image)

As well as H₂O, H₂ also begins to form above the partial oxidation zone (pyrolysis and oxidative pyrolysis) and then the mole fraction decreases in the partial oxidant zone due to the hydrogen oxidation reaction. Afterwards, increase again in the reduction zone due to the water-gas and steam reforming reactions. CH₄ began to take shape after Methanation reaction in the reduction zone while CO has begun to be produced from the partial oxidation reaction of charcoal and boudourd reaction in the reduction zone. From the CFD simulation results, the maximum syngas composition obtained for CO, H₂, CH₄, CO₂, and H₂O were 30.85%, 16.74%, 2.25%, 0.5%, and 0.57%, respectively with low heating value 5.323 kJ/kg. When compared with syngas composition from single stage gasifier, the amount of CO
produced is greater because the area of oxidative pyrolysis occurs partial oxidation of carbon with a limited amount of air in that zone. In addition, CO increases also occur because of high reaction temperatures in partial oxidation zones.

4. Conclusion
Based on the results of the CFD analysis can be concluded as follows:

- Oxidative pyrolysis increases temperature of area above the partial oxidation zone to 785°C to form a new combustion zone (oxidative pyrolysis zone). The heat energy for the endothermal reaction (drying and pyrolysis) is obtained from the heat energy released by the oxidative pyrolysis zone. Due to the existence of a new zone changes the thickness of the pyrolysis layer becomes thicker and the drying zone becomes thinner so that the time required for the drying process and produce the flammable gas becomes shorter.
- Temperature increase in the oxidative pyrolysis zone and the partial oxidation increase the percentage mole of the flammable gas fraction especially CO up to 30.85%.

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