Numerical study of the effect of oxidation zone inlet air temperature variation on municipal solid waste pellet gasification process on downdraft type reactor characteristics

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Abstract. Gasification is an efficient technology to extract energy from MSW biomass into energy in the form of syngas. One of the most influential parameters to improve syngas quality is temperature, so the development of the design and operation of the downdraft type reactor is done by heating the inlet air of the oxidation zone through an external heater. Research with numerical studies was carried out on the effect of the inlet air in the oxidation zone to determine the temperature distribution and syngas composition along the reactor. Based on experimental research, heating the inlet air of the oxidation zone with external heaters in this study was carried out with 5 temperature variations, namely 80 °C, 110 °C, 150 °C, 180 °C, and 200 °C. 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). The results obtained from this study were that the highest air temperature was obtained at 200°C at 1004 °C in the oxidation zone. The composition of syngas CO, H₂, and CH₄ at temperature increases of 80-200 °C increased from 21.64%, 9.24%, and 2.86% to 22.65%, 10.49%, and 3.10%. Then increasing the LHV syngas from 4,757.20 kJ/m³ to 5,106.02 kJ/m³. Cold gas efficiency increased from 72.17% to 79.31%.

1. Introduction

Increased energy consumption occurs every year in the 2000-2014 period. The average annual growth for the period 2000-2014 was 3.99% in 2014. Besides that, oil production in Indonesia since 2010-2014 decreased by around 4.41% [1]. If this is not considered, it will lead to a serious energy crisis, so that efforts are needed to cover the energy crisis by developing new renewable energy as an alternative energy.

Waste management with technology has great potential to become renewable energy. This is because the amount of landfill increase in Indonesia itself is known to have reached 175,000 tons/day or equivalent to 64 million tons/year [2]. The technology that makes it possible to convert waste into renewable energy is by using a thermochemical process, [3]. Municipal Solid Waste (MSW) is a solid waste produced by urban communities, obtained from landfills (TPA). The latest method of processing MSW is by turning it into a pellet shape. Changing the shape into pellets has the advantage of reducing moisture content where the moisture content of MSW pellets is more homogeneous than not being
converted into pellets [4].

Experimental research on the gasification process using downdraft type reactors has been carried out by Depi Rustam [5], Aji Triyanto [6], Rizki Wase [7] and Irfan Maulana [8] in 2017 with MSW biomass raw material. The study was carried out by [5] with gasification characterization which showed the effect of inlet air heating on the oxidation zone with external heating on the temperature distribution of the reactor, especially the oxidation zone. The study showed that the presence of air heating from 80 °C to 200 °C was able to increase the temperature of the oxidation zone from 818 °C to 942 °C and improve the quality of syngas, which increased LHV syngas from 4227.99 kJ/m$^3$ to 4609.99 kJ/m$^3$.

Gasification research has been carried out numerically before by several researchers, namely [9], who have also examined the simulation of rice husk gasification on downdraft type glue. The study only observed the 2-dimensional plane of the reactor and varied the AFR which could maximize the efficiency of the gasification process. Next is the design of a rice husk gasification reactor in a downdraft type reactor, developed by [10] with a simulation of downdraft type Computational Fluid Dynamics (CFD) gas with rice husk biomass. The study observed in 3 dimensions with variations in throat angle and inlet air. Then based on the results of the research [5] it is known that the addition of an external air heater is needed to be able to achieve the desired optimum temperature.

Therefore, in this study modeling and simulation will be carried out with variations in the addition of an external air heater before the air enters the internal heater which will be supplied to the downdraft reactor type oxidation zone with MSW pellet raw material. In this study, the gasification process that occurs in the reactor will be numerically modeled using the standard k-epsilon, Radiation P1, the transport species model with turbulence used is finite-rate/eddy-dissipation, and Discrete Phase Model (DPM). The data from the experimental research will be used as a validation of the results of gasification research using numerical models.

2. Formatting the title, authors and affiliations
Modeling and simulation in this study using CFD software. The steps taken are:

2.1. Pre-processing
This stage includes several sub-stages, namely making geometry, making meshing, and determining the modeling domain.

![Figure 1. Reactor design](image1.png)  
![Figure 2. Meshing on the reactor](image2.png)
2.2. Processing
Processing is setting up the Ansys Fluent 16 software. Some of the settings that will be carried out include models, materials, boundary conditions.
   a) Models
      The P1 radiation model was used in this study [11]. The finite rate/Eddy dissipation reaction model is used [12]. The viscous turbulence model used is the k-epsilon model, [12]. The reaction model in this study was taken from several sources summarized in table 1.
   b) Materials
      The input value for ultimate and proximate analysis is shown in Table 1.
   c) Boundary Condition
      In this study, boundary conditions are attached to Table 2

2.3. Post-processing
Observations will be made on each variation. Qualitative data in the form of contours taken in vertical sections (z-center reactor and x-center reactor) and horizontal cross section on each reactor section y (drying zone, pyrolysis zone, partial combustion zone, reduction zone)

3. Results and Discussion
Characteristics of the gasification process in a study, one of which was obtained through variations in air temperature in the oxidation zone inlet. Five variations of inlet air temperature were carried out with numerical methods in this study, namely: 80 °C, 110 °C, 150 °C, 180 °C, and 200 °C. Through proximate and ultimate test data, the composition of each element (C, H, O, N, S) and the content of moisture, ash, fix carbon, volatile, so that coal particles as input for experimental testing can be assumed as MSW particles.

| Table 1. Basic characteristics of the pellet MSW |
|------------------------------------------------|
| Proximate analysis | (% wt) |
| Moisture content | 9.82 |
| Ash content | 14.71 |
| Volatile matter | 65.78 |
| Fixed carbon | 9.69 |
| Ultimate analysis | (% wt) |
| C | 39.83 |
| H | 6.7 |
| O | 38.11 |
| N | 0.35 |
| S | 0.14 |
| HHV | 13.84 MJ/kg |

| Table 2. Boundary condition settings used in modeling |
|-----------------------------------------------------|
| Boundary Condition | Type | Value |
| Air inlet | Mass flow inlet | ṁ : 0.003032 kg/s |
| Biomass Inlet | Mass flow inlet | ṁ : 0.00309 kg/s |
| Reactor | Pressure-outlet | T : 80,110,150,180,200°C |
| Syngas Outlet | Wall | Material : Steel |
3.1. Analysis of Temperature Distribution Throughout the Reactor

Temperature distribution along the reactor is shown to determine the effect of air heating temperature. The temperature value of each zone is taken using the Report-Surface integral-Area weighted average menu in the thermocouple position that corresponds to the experimental method. The Area weighted average menu is used to take the average temperature value in the Y coordinate section. To determine the boundaries between zones in the gasification process, the graph in Figure 3 is obtained with 12 starting points taken at reactor height: 0.2 m, 0.3 m, 0.4 m, 0.5 m, 0, 6 m, 0.7 m, 0.8 m, 0.9 m, 1 m, 1.1 m, 1.2 m, and 1.3 m.

Based on Figure 3, it can be seen that the temperature in the reactor for each scenario tends to have a uniform pattern. At an altitude of 104 cm from the bottom of the reactor, the measured temperature is 150 °C, indicating that the height is at the boundary between the drying zone and the pyrolysis zone for the addition of an air temperature of 80 °C [13]. The addition of air temperature at 110 °C, 150 °C, 180 °C, and 200 °C, resulted in a shift in the drying zone at a temperature of 150 °C.

**Table 3.** The reactions involved in the gasification

| Reaction | \( \Delta H \) (kJ/kmol) | A | E (J/kmol) | Source |
|----------|--------------------------|---|------------|--------|
| C(s) + 0.5O\(_2\)(g) \( \rightarrow \) CO(g) | R1 \(-110.5\) | 0.052 | \(6.1 \times 10^7\) | [16] |
| C(s) + CO\(_2\)(g) \( \rightarrow \) 2CO(g) | R2 \(+172\) | 0.00732 | \(1.125 \times 10^8\) | [16] |
| C(s) + H\(_2\)O (g) \( \rightarrow \) CO(g) + H\(_2\) (g) | R3 \(+131.4\) | 0.00782 | \(1.15 \times 10^8\) | [16] |
| C(s) + 2H\(_2\) (g) \( \rightarrow \) CH\(_4\)(g) | R4 \(-75\) | 0.12 | \(1.7 \times 10^7\) | [17] |
| CO(g) + 0.5 O\(_2\)(g) \( \rightarrow \) CO\(_2\)(g) | R5 \(-283.1\) | \(2.2 \times 10^{12}\) | \(1.67 \times 10^8\) | [18] |
| H\(_2\)(g) + 0.5 O\(_2\)(g) \( \rightarrow \) H\(_2\)O (g) | R6 \(-242\) | \(6.8 \times 10^{12}\) | \(1.68 \times 10^8\) | [19] |
| CH\(_4\)(g) + 0.5 O\(_2\)(g) \( \rightarrow \) CO(g) + 2H\(_2\) (g) | R7 \(-36\) | \(1 \times 10^{15}\) | \(1 \times 10^8\) | [14] |
| CO(g) + H\(_2\)O (g) \( \rightarrow \) CO\(_2\)(g) + H\(_2\) (g) | R8 \(-41\) | \(2.75 \times 10^{10}\) | \(6.1 \times 10^7\) | [17] |
| 2CO(g) + 2H\(_2\) (g) \( \rightarrow \) CH\(_4\)(g) + CO\(_2\) (g) | R9 \(-247\) | \(1 \times 10^{10}\) | \(1 \times 10^8\) | [14] |
°C. So that the boundary between the drying zone and the pyrolysis zone with the addition of an inlet air temperature of 80 - 200 °C is at an altitude of 104 cm to 110 cm. In the drying zone the water content in the fuel is evaporated into steam. The closer the temperature is 150 °C, the drying process will get better. Menurut [14] batas zona pirolisis akan terjadi pada kisaran suhu 150-700 °C. It can be seen that figure 3, the addition of air temperature variation 80 - 200 °C shows that in the height range 60 - 65 cm is the limit of the pyrolysis zone, which produces products in the form of hydrogen, carbon monoxide, carbon dioxide, hydrocarbons, and char.

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Figure 4. Zone boundaries in a downdraft reactor with a variation of 200 °C air temperature and T1-T8 thermocouple position

At an altitude of 50 cm with air temperature variations; 80 - 200 °C, producing temperatures at the bottom of the reactor in a row of value; 830 - 1004 °C. These values show the maximum temperature in the partial oxidation zone. According to [14] the oxidation zone will occur in the temperature range of 700-1500 °C, so that the partial oxidation temperature in this study is appropriate because it is still in that range. In the partial oxidation zone exothermic reactions occur (char combustion, partial oxidation, hydrogen combustion) which produce carbon dioxide (CO2), carbon monoxide (CO), and water vapor (H2O) products. According to [15], the reduction zone operates at a temperature range of 400-700 °C. That way you can know the boundary between the partial oxidation zone and the reduction zone for air temperature variations; 80 - 200 °C, respectively in the height range; 41 - 37 cm. The reduction zone is shown at a height of 30 cm with air temperature variations; 80-200 °C, producing temperatures in a row valued at 520 - 580 °C. Thus the large maximum zone of the gasification process in the reactor is known, namely at a variation of 200 °C air temperature, among others; drying zone at an altitude between 110-130 cm, pyrolysis zone at an altitude between 65-110 cm, oxidation zone at an altitude between 37-65 cm, and a reduction zone at altitudes between 20-37 cm.

The boundaries between zones in the gasification process based on this numerical method can evaluate and provide recommendations from the experimental method to determine the position of the thermocouple with the same reactor. Thermocouple placement in the experimental method include: T1 = 1.30 m; T2 = 1.14 m; T3 = 1 m; T4 = 0.7 m; T5 = 0.6 m; T6 = 0.5 m; T7 = 0.3 m; T8 = 0.2 m. In Figure 4 shows that the placement of thermocouples in the drying zone for T1 is appropriate because to measure the temperature at the end of the reactor. The recommendations for the T2 position for experimental research are then transferred to a height of 1.2 m, where the position can be representative of the temperature in the drying zone. In the pyrolysis zone of T3 and T4 it is recommended to change the position of the thermocouple at an altitude of 0.875 m, where it can represent the pyrolysis zone temperature. T5 and T6 can be recommended for placing a thermocouple at a height of 0.51 m as a temperature alternative to the oxidation zone. T7 at a height of 0.3 m can already be used as a
representative temperature in the reduction zone. While T8 is known as a temperature representative in the syngas outlet zone.

The results in the drying and pyrolysis zones in Figure 5 show that the temperature distribution is less symmetrical in the Z coordinate section as shown in Figure 5 (a). The indications that cause this asymmetry are the reactor design factors. In the drying zone, the biomass input geometry is in an asymmetrical position in the middle plane z and has a diameter that is different from the reactor wall diameter, so that the temperature distribution is not evenly distributed throughout the reactor wall. If the reactor design is replaced by making the position of the biomass input in the middle of the reactor indicated to produce a temperature difference will be very small.

**Tabel 4. Syngas composition from the results of numerical methods**

| $T_{air}$ (°C) | CO (% vol) | H$_2$ (% vol) | CH$_4$ (% vol) | CO$_2$ (% vol) | N$_2$ (% vol) | O$_2$ (% vol) |
|----------------|------------|---------------|----------------|----------------|---------------|---------------|
| 80             | 21,64      | 9,24          | 2,86           | 2,62           | 61,6          | 2,04          |
| 110            | 21,8       | 9,45          | 2,9            | 2,3            | 61,6          | 1,94          |
| 150            | 22,12      | 9,87          | 2,98           | 1,87           | 61,5          | 1,67          |
| 180            | 22,43      | 10,28         | 3,05           | 1,52           | 61,4          | 1,32          |
| 200            | 22,65      | 10,5          | 3,1            | 1,34           | 61,4          | 1,01          |

*Figure 6. Average distribution of volumetric percentages CO along the reactor for each variation*
3.2 Analysis of flammable syngas composition

Based on the results of Table 5 the composition of flammable syngas generated by the average numerical method has increased. In CO compounds, an increase of 1.01% was obtained from the inlet air temperature of 80 °C to 200 °C. Similarly, H₂ and CH₄ compounds obtained increased by 1.26% and 0.24%. This proves that if the inlet air temperature is increased, it will improve the quality of syngas by increasing the composition of flammable syngas, namely CO, H₂, and CH₄. The largest non-flammable syngas composition is N₂, because the gasifying agent used is free air containing O₂ and N₂ compounds. Values in CO₂ and O₂ compounds tend to be small and decrease from 80 °C to 200 °C inlet air temperature. It can be indicated that the small value of the CO₂ compound is reduced by Boudouard reaction and the reversible reaction of R8 in the reduction zone and the faster the reaction as the inlet air temperature is added. O₂ compounds look small, indicating that the gasification process works optimally. Decreasing O₂ composition in syngas as an effect of increasing the inlet air temperature of the oxidation zone shows that the increase in air temperature makes O₂ more reactive.

3.2.1 Volumetric Analysis of CO Distribution. Temperature comparison chart along the reactor with an average percentage of volumetric CO for 5 variations in the addition of inlet air temperature, each section of Y coordinate with the thermocouple position according to the experimental method (T1-T8).

When viewed from a graph of the average distribution of CO volumetric percentages shown in Figure 6, CO compounds in the drying zone are not significant. This is because the modeling used by the reactions in Table 1 did not occur in the drying zone. According to [15] to find out the drying process must be modeled with the multiphase model and use UDF (user define function) on the fluent. However, this study did not use the multiphase and UDF models, so that the drying process in the reactor could not be seen.

The pyrolysis zone is quite suitable because of the devolatilization process which breaks down the dried MSW pellets into several gas products, one of which is CO gas. In Figure 6 the percentage value of volumetric CO in the pyrolysis zone (T3 and T4) is less than 20% where in the range of zones the CO produced product is 10-20 mole%, (Basu, 2012). Then in the partial oxidation zone (T5 and T6) by increasing the air temperature from 80-200 °C, the percentage value of CO volumetric decreases. This is because CO reacts with oxygen (R5) to produce CO₂ (CO (g) + 0.5O₂ (g) → CO₂ (g)). Besides that in this zone CO can also be produced through partial combustion (R1), so that the product of this partial combustion will be continued with a reaction in the reduction zone. The partial combustion reaction (C(s) + 0.5O₂ (g) → CO (g)) which produces this CO product is a slow reaction [2]. If we review in more detail the air temperature variation of 200 °C, the difference in the percentage value of volumetric CO between T5 and T6 is 3.92%, which is greater than the air temperature variation of 80 °C which is 3.85%. This shows that the partial oxidation process is more reactive with higher air temperature, so the reaction in the zone will be faster.

The significant increase in CO volumetric percentage value from T6 to T7 shows that in the reduction zone many produce CO. This is because there are 3 reactions that produce CO, which are (1) boudouard reaction (R1) which is to change the char that reacts with CO₂ to CO, (2) the water-gas reaction (R3) which is to change the char that reacts with H₂O to CO and H₂, (3) steam reforming reaction (R7) which converts CH₄ to CO and H₂ because it reacts with O₂. While at T8, CO volumetric percentage value also increased but not too significant.

3.2.2 Volumetric Analysis of H₂ Distribution. If viewed from the graph of the average distribution of volumetric H₂ percentage, the drying zone of H₂ gas is not significant. This is because the modeling reactions used in Table 1 do not occur in the drying zone. In the pyrolysis zone there is a devolatilization process which breaks the dried MSW pellets into several gas products, one of which is H₂. This is appropriate, because up to a temperature of 600 °C H₂ gas will experience an increase due to the shift reaction, and will decrease when above 600 °C [14].

Based on the results of Table 5 the composition of flammable syngas generated by the average numerical method has increased. In CO compounds, an increase of 1.01% was obtained from the inlet air temperature of 80 °C to 200 °C. Similarly, H₂ and CH₄ compounds obtained increased by 1.26% and 0.24%. This proves that if the inlet air temperature is increased, it will improve the quality of syngas by increasing the composition of flammable syngas, namely CO, H₂, and CH₄. The largest non-flammable syngas composition is N₂, because the gasifying agent used is free air containing O₂ and N₂ compounds. Values in CO₂ and O₂ compounds tend to be small and decrease from 80 °C to 200 °C inlet air temperature. It can be indicated that the small value of the CO₂ compound is reduced by Boudouard reaction and the reversible reaction of R8 in the reduction zone and the faster the reaction as the inlet air temperature is added. O₂ compounds look small, indicating that the gasification process works optimally. Decreasing O₂ composition in syngas as an effect of increasing the inlet air temperature of the oxidation zone shows that the increase in air temperature makes O₂ more reactive.
Then in the partial oxidation zone (T5 and T6) by increasing the air temperature from 80 to 200 °C, the percentage value of volumetric H\textsubscript{2} decreases. This happens because H\textsubscript{2} reacts with oxygen (R6) to produce H\textsubscript{2}O. H\textsubscript{2} also decreases to the reduction zone limit, because it reacts with CO (R9) so that it forms CH\textsubscript{4} and CO\textsubscript{2}. If viewed in more detail from Figure 7 variations in air temperature 200 °C the difference in volumetric H\textsubscript{2} percentage value between T5 and T6 is 0.21% greater than the air temperature variation of 80 °C which is 0.18%. This shows that the H\textsubscript{2} combustion process is more reactive with the addition of a higher air temperature, so the reaction in the zone will be faster. A significant increase in the volumetric percentage value of H\textsubscript{2} from T6 to T7 indicates that the reduction zone produces a lot of H\textsubscript{2}. There are two reactions that produce H\textsubscript{2} in the reduction zone. The first is the shift reaction (R8) which converts CO that reacts with H\textsubscript{2}O to H\textsubscript{2} and CO\textsubscript{2}. The second reaction is water-gas (R3) which converts the char that reacts with H\textsubscript{2}O to CO and H\textsubscript{2}. The third reaction is methane gasification (R7) which converts CH\textsubscript{4} to CO and H\textsubscript{2} because it reacts with O\textsubscript{2}.

3.2.3 Volumetric Analysis of CH\textsubscript{4} Distribution. Adding T9 point at 0.4 m height to find out more details of CH\textsubscript{4} percentage volumetric average distribution. When viewed from the average distribution of volumetric CH\textsubscript{4} percentage shown in Figure 4.12, the CH\textsubscript{4} gas drying zone is not significant. This is because in this study with the modeling used the reactions in table 1 did not occur in the drying zone. In the pyrolysis zone, CH\textsubscript{4} increases. This is because in the pyrolysis zone there is a devolatilization process which breaks the dried MSW pellets into several gas products, one of which is CH\textsubscript{4}. CH\textsubscript{4} compounds also increase to the limit between the partial oxidation zone and the reduction (T9). This is because at the boundary between these zones CH\textsubscript{4} is produced from methanation reaction (R9). That is the reaction of CO and H\textsubscript{2} which produces CH\textsubscript{4} and CO\textsubscript{2}.

**Figure 7.** Average distribution of volumetric percentages H\textsubscript{2} along the reactor for each variation

**Figure 8.** Average distribution of volumetric percentages CH\textsubscript{4} along the reactor for each variation
3.3 **Analysis of Cold Gas Efficiency Gasification Process**

Figure 9 shows that heating the air temperature from 80-200 °C can increase cold gas efficiency by 7.34% with a relatively linear increase. This increase was not only influenced by the increase in LHV in syngas, but also influenced by the mass flow rate of biomass (MSW pellet) and the syngas mass flow rate.

![Figure 9. Effect of air temperature on cold gas efficiency](image)

Research conducted by experimental methods shows that with an increase in air temperature from 80-200 °C able to increase cold gas efficiency can increase by 14%, from 47% to 61%. This difference is quite large because the increase is not only affected by an increase in LHV in syngas, but also influenced by the mass flow rate of biomass (MSW pellet) and syngas mass flow rate. The influencing factor is in addition to measuring the syngas mass flow rate which is carried out using the experimental method, measurements are taken from the outputs in the form of char and ash. While the limitation of the problem in the study with the numerical method of output measured only syngas.

4. **Conclusion**

Characterization of the downdraft type gasification reactor with the addition of inlet air temperature variations in the partial oxidation zone from 80 °C to 200 °C are as follows:

1. Temperature distribution of each gasification zone increases;
   - zone drying increases (T2) from 130 °C to 140 °C
   - the pyrolysis zone increases (T4) from 498 °C to 578 °C
   - the partial oxidation zone increases (T6) from 830 °C to 1004 °C zona reduksi meningkat (T7) dari 520°C sampai 580°C
2. Volumetric percentages on flammable syngas (CO, H₂, and CH₄) increased from 21.64%, 9.24%, and 2.86% to 22.65%, 10.49%, and 3.10%.
3. Cold gas efficiency increased from 72.17% to 79.51%.

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