CFD Letters

Journal homepage:
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ISSN: 2180-1363

CFD Simulation Analysis of Sub-Component in Municipal Solid Waste Gasification Using Plasma Downdraft Technique

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ARTICLE INFO

Article history:
Received 16 June 2022
Received in revised form 16 July 2022
Accepted 31 July 2022
Available online 31 August 2022

Keywords:
Gasification; Plasma; Downdraft; Food waste, Paper; Yard waste; Syngas composition

ABSTRACT

Plasma gasification technology is one of the potential methods to decompose dangerous wastes and turn them into non-leachable slag due to it greater energy efficiency and bottom ash prevention concerns. However, a fundamental study of CFD simulation on the reaction flow characteristic using the operational of plasma gasification process was scarce. The present study aims to investigate the gasification characteristic of municipal solid waste (MSW) component including food waste, paper, and yard waste to produce synthesis gas using a 3-dimensional CFD simulation method in the downdraft plasma gasifier. The reaction model of non-premixed combustion, Euler-Lagrangian approach and K- ε turbulence model was used as a setup parameter. Plasma being consider as hot gas with 1173K, coal as 293K and air inlet on 673K. Flowrate of feedstocks, plasma gas flow and air flowrate are set to 0.029 kg/s, 0.0438kg/s, and 0.0029kg/s respectively. Based on the result and comparison between those feedstocks, food waste typically produced higher CH_4, CO, and CO_2 than paper and yard. Yard wastes yield the highest H_2 content which consist of 0.544 mole fraction, with 539.24% higher than food waste and 79.76% higher than paper. The result showed that gasification of different component from MSW produced different characteristic of syngas based on the properties of the feedstock.

1. Introduction

Municipal solid waste (MSW) consists primarily of waste commonly disposed from residential life, business, and administrative operations. Food waste, paper, plastic, glass, textile scrap material, timber, and other are contains in MSW [1]. Malaysia is currently experiencing a problem-related with municipal solid waste (MSW) treatment. In 2020, the municipal solid waste is estimated to reach 30,000 metric tons and increase by 9% when 2030 [2]. With that amount of MSW, Malaysia can produce a significant number of bio-products for a green economy with gasification technology [3]. But in Malaysia waste management, MSW is just being treated as a useless product and mostly dump into landfill area or send to incineration.

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https://doi.org/10.37934/cfdl.14.8.6370

Waste was not properly treated in Malaysia as almost 89% of the municipal solid waste are directly sent into landfills. 50% of landfills in Malaysia are open for dumpling, 30% for buried, 12% are controlled landfills, 5% for sanitary landfills without leachate treatment and another 5% is with leachate treatment. With this situation continue for more ten years, the dumping area will expand till 80% of all the dumping sites will be full capacities [4,5].

Plasma gasification technology is one of the potential alternatives to decompose dangerous wastes and turn them into non-leachable slag. It has recently developed and used as a valuable and efficient tool for solid waste disposal. Plasma gasification is benefited compared to conventional gasification in terms of produced syngas which is higher in heating value, greater energy efficiency and bottom ash prevention concerns [6]. Plasma gasification is a process that promoted waste to be exposed in the extreme thermal condition of more than 1000°C plasma heat. The multiple steps in plasma gasification involved a process of waste handling, plasma reaction, gas cleaning, and conversion unit. The waste is typically gasify using plasma heat with the assistant of oxidant element as to convert it into syngas [7]. The generator used for plasma gasification are commonly called as microwave plasma torch and transferred or non-transferred arc plasma torch [8,9]. With high electricity and fluid, plasma can be heat up to 10,000 K in the gasifier. There are several types of mediums used for plasma including air, water, steam, nitrogen, carbon dioxide, or mixture of the medium [9].

Work on plasma gasification is rarely conducted by previous study using CFD simulation method. Investigation on the gasification of MWS is also scarce. Few works on MSW gasification and plasma technology are described as follows. Ibrahimoglu and Yilmazoglu [10] study the plasma downdraft gasification simulation by using Eulerian–Lagrangian and a turbulence model of Standard k-ε model. The result of the simulation shows that the syngas was decreased from 1536.6 kcal/m^3 to 751.8 kcal/m^3 as equivalence ratio value increased from 0.20 to 0.45. Mazzoni *et al.,* [11] study the simulation of downdraft gasification which was gasified with plasma gas using Euler-Euler method and k- ε model turbulence model. The result found that Plasma gasification has a better performance than entrained flow with higher mole fraction of CO and H_2 in syngas. Ismail *et al.,* [6] use Euler-Euler multiphase mathematical modelling to study the effect of equivalence ratio (ER) and steam to fuel ratio (SFR) on the composition of produced syngas. The results found that composition of H_2 and CO is slightly decrease and increase respectively as the equivalence ratio increase. Shehzad *et al.,* [12] investigated the characteristic of MSW gasification in 30MW plant using Aspen Plus simulation. The results showed that gasifier temperature has very strong impact on the syngas composition. Yet greater heat put relatively caused the great cost. Fortunato *et al.,* [13] used standard k-ε model as a turbulence model to simulate the gasification of sawdust, sewage sludge and corn straw. The results found that the simulation model was capable to run with good agreement derived from few types of biomasses.

From the review of previous study, analysis which specifically used MSW or any component of MSW in plasma gasification reactor using CFD simulation method was not thoroughly covered by previous research. Thus, the present paper aims to investigate the effect of plasma reaction on the quality of syngas produced from the gasification of MSW by using CFD simulation analysis.

2. Methodology

2.1 Materials Preparation

The feedstocks used in this simulation study were the sub-component of Municipal Solid Waste (MSW) including food waste, paper, and yard waste. Table 1 showed the solid properties of food waste, paper and yard waste based on the data from ref. [14]. Moisture content for food waste was higher compared to another component which was 70%. Whereas paper was attributed higher volatile matter which was 75.9% compared to another component. Moisture content and volatile matter were typically a primary indication of high production rate of H_2 and tar respectively [15].

Table 1
Properties of food waste, paper and yard waste [14]

Proximate Analysis (%)			
	Food waste	Paper	Yard waste
Moisture content	70	10.2	60
Ash content	5.0	5.4	0.5
Volatile matter content	21.4	75.9	30
Fixed carbon content	3.6	8.4	9.5
Ultimate Analysis (%)			
	Food waste	Paper	Yard waste
C	73.0	43.3	46.0
H	11.5	5.8	6.0
O	14.8	44.3	38.0
N	0.4	0.3	3.4
S	0.1	0.2	0.3
Ash	0.2	6	6.3

2.2 Turbulence Model

The present simulation was used standard of K - ε model for turbulence model as it is typically demonstrated good results in practice for internal flow [10,16,17]. In addition, K - ε model also economical in terms of computational time [18]. The turbulence model was based on the equation of kinetic energy, k and dissipation rate, ε which were formulated as in Eq. (1) and Eq. (2):

$$\frac{\partial}{\partial t}(pk) + \frac{\partial}{\partial X_j}(pkn_i) = \frac{\partial}{\partial X_j}\left(\left(u_{+\frac{u_t}{\sigma k}}\right)\frac{\partial k}{\partial x_i}\right) + G_k + G_b - p_E - Y_M + sk \quad (1)$$

$$\frac{\partial}{\partial t}(p\varepsilon) + \frac{\partial}{\partial X_i}(p\varepsilon u) = \frac{\partial}{\partial X_j}\left(\left(\mu_{+\frac{ut}{\sigma_t}}\right)\frac{\partial \varepsilon}{\partial x_i}\right) + c_1\frac{\varepsilon}{k}(G_k + c_3 G_b) - c_2 p\frac{\varepsilon^2}{k} + s_\varepsilon \quad (2)$$

Where Gk is the velocity gradients for the turbulence model, Gb is the generation of buoyancy. YM is representing the contribution of the fluctuating and C1, C2, C3, are constant. σk and σt are represent k and ε as the Prandtl number. For the Sk and Sε is for user to define the source term. The value of C1, C2, C3, σk, and σt already constant as 1.44, 1.92, 0.09, 1 and 1.3.

2.3 Euler-Lagrangian Approach

This simulation was used Euler–Lagrangian approach where solid phase or gas phase are consisting in individual particle. Solid gas flow can also use Euler - Euler approach or Two Fluid Model which contain both the solid and gas phases. But the limitation of solid particle getting tracked is making the approach feasible for dilute solid phase flow.

2.4 Mesh Construction

The development of mesh was conducted using the Ansys workbench mesh platform. The reactor model developed based on different zone including drying, pyrolysis, oxidation and reduction. Inlet of plasma and oxidant were located at pyrolysis and oxidation zone in which the density of mesh was highly concentrated as shown in Figure 1. The mesh parameter was set-up with CFD physics and fluent solver preference. The linear element order was also included with the size of 100mm. Mesh defeaturing and proximity were used as the size function for the element with non-activated adaptive sizing. The maximum sized of element was set as 200mm. Inflation transition ratio was set as 0.272 with 5 minimum layers and growth rate of 1.2. The generated mesh of the model produced 26756 nodes and 89805 elements. The mesh quality of skewness and orthogonality was reached an average of 0.27237 and 0.72525.

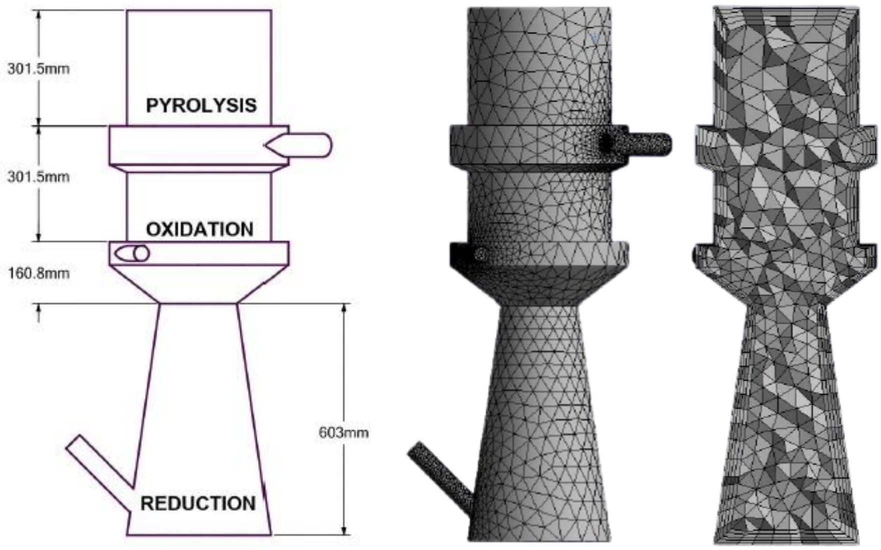

Fig. 1. Gasification zone and structure tetrahedron mesh

2.5 Setup Parameter

The simulation setup parameter was primarily using coal as feedstock and validated with the previous study [10,16]. The validated setup model was then applied for different type of MSW waste. Thus, the setup parameter was identical for those feedstocks of food waste, paper and yard waste. The gravity force value was set at -9.81 m/s^2. The energy equation was also implemented for radiation purpose. Other setup parameters such as plasma flowrate, gasifying agent flowrate and feedstock flowrate were presented as in Table 2 shown.

Table 2
Setup parameter of simulation analysis

Gasifier	Fixed Bed Downdraft gasifier
Plasma temperature	1173 K
Plasma flowrate	0.0438 kg/s
Gasifier agent	Air
Gasifier agent flowrate	0.0029 kg/s
Feedstock flowrate	0.02908 kg/s
Turbulence model	Standard k-ε model
Approach	Euler - Langrangian

The reaction model of non-premixed combustion was used in this study. The Injection of fuel was only applied at feeding surface for discrete phase model. Rosman method was used to control the surface injection area. Discrete random walk method was set to 25 as recommended. The number of iterations was set for 5000 for the first trial as to achieved the convergence condition. The iteration was typically converged at less than 2000. SIMPLE scheme deployed in pressure-velocity coupling. All of the spatial discretization changes to first order upwind and gradient as least squared cell based.

3. Results

3.1 Model Validation

Composition of syngas is typically consisted of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and methane (CH_4). The volume fraction in syngas component may varies due to some factors including feedstock, gasifying agent and reactor. Simulation model for the present study was set as in Table 2. Those setups were then being validated with the previous study from Ibrahimoglu *et al.,* [16]. The deviation between the present result of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) with Ibrahimoglu *et al.,* [16] was then analysed as shown in Figure 2. The deviation value between those results were calculated using Eq. (3).

$$\text{Error percentage, \%} = \frac{|\text{present mole fraction} - \text{previous mole fraction}|}{\text{Previous mole fraction}} \times 100\% \quad (3)$$

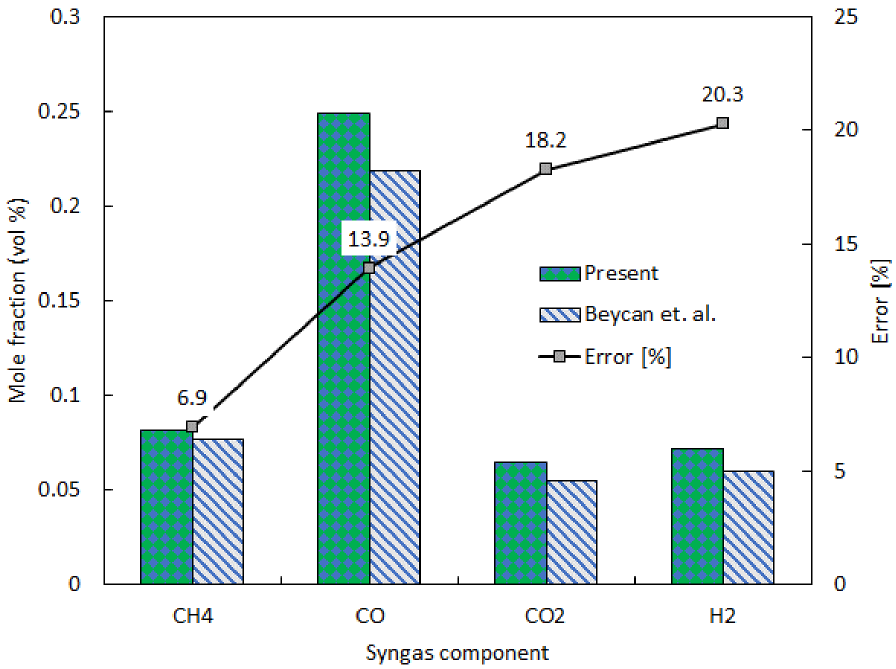

Fig. 2. Validation of mole fraction for the current result with previous study

Figure 2 showed that the results of present study was in good agreement with Ibrahimoglu *et al.,* [16] as the error percentage was less or equal 20% for all the syngas components. The deviation was only 6.9%, 13.9%, 18.2% and 20% for CH_4, CO, CO_2 and H_2 respectively. The deviation seems to cause by the usage of non-premixed combustion model in which the reaction kinetic of species does not require a source term of governing transport equation. Hence, the produced species might typically demonstrate different mixture fraction as compared to species transport model which was implemented by Ibrahimoglu *et al.,* [16].

3.2 Effect of Different Type of Feedstock

Comparative study has been conducted for the produced syngas in the reactor between the feedstocks of food waste, paper and yard waste as shown in Figure 3. The analysis was only focused in oxidation zone as the main reaction occur in this region. The study also only considered the species component of combustible gas which contributed to the significant effect of heating value amount including CO H_2 and CH_4. The distribution of species component was also compared with the temperature distribution in the reactor.

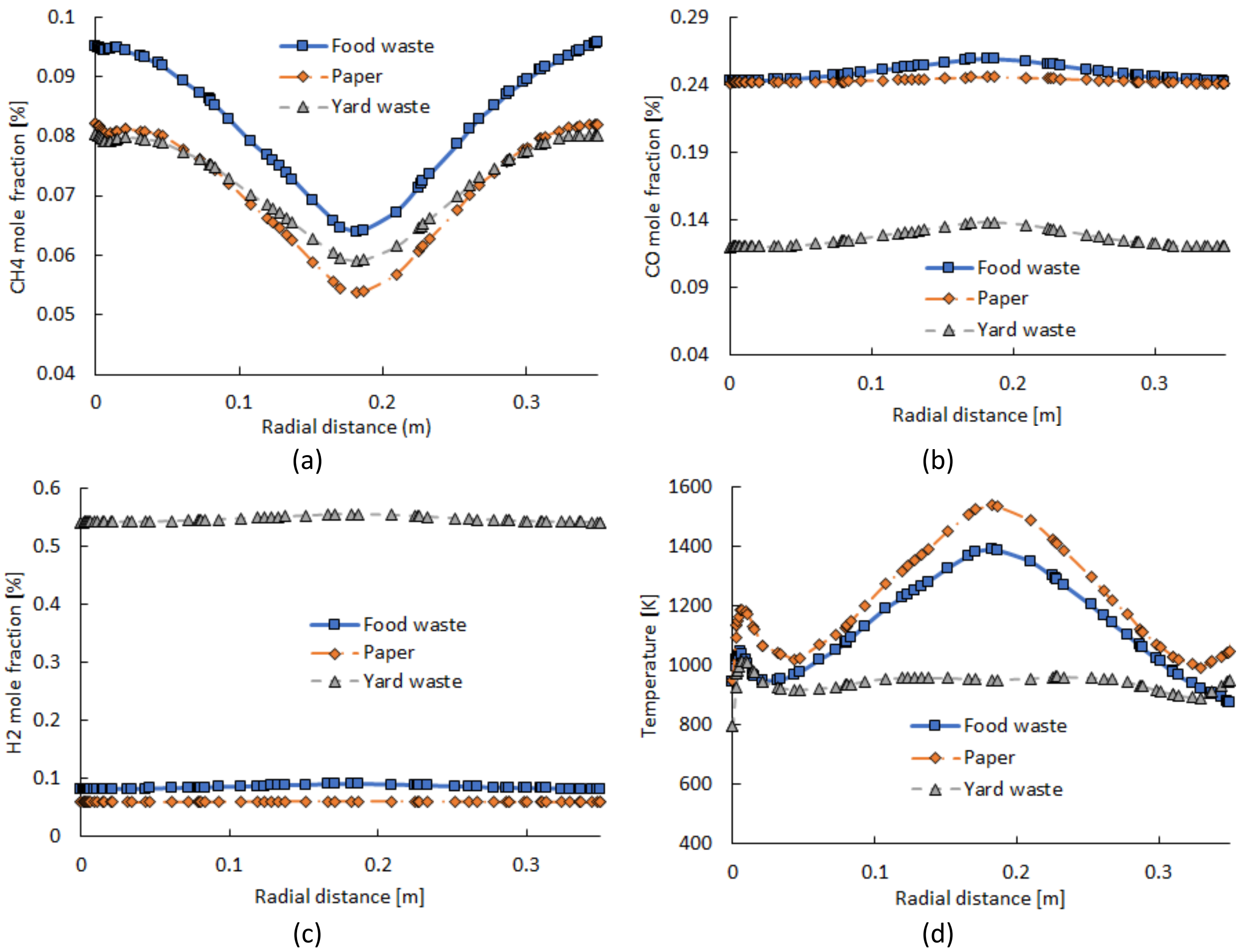

Fig. 3. Comparison of syngas composition between food waste, paper and yard waste in oxidation zone for the component of (a) CH_4, (b) CO, (c) H_2, and (d) temperature

Figure 3(a) showed that the composition of CH_4 slightly higher for food waste as compared to paper and yard waste. The moisture of food waste seems to promote the production of CH_4 via the methanation and steam-methane reforming reaction. Figure 3(b) showed that food waste and paper produced higher CO compared to yard waste. The produced species component was straight forward as food waste and paper attributed higher carbon C element, thus the produced CO also relatively higher via the reaction of water-gas and Boudouard [19]. Figure 3(c) showed that yard waste produced a significant higher H_2 content compared to food waste and paper. The aforementioned result also related with distribution of temperature in Figure 3(d). The temperature distribution for food waste and paper was higher compared yard waste due to high content of radical C-element and low moisture content respectively. The high carbon content in food waste and low moisture content in paper contributed to the high combustible fuel characteristic hence increase the rate of decomposition for radical carbon of C element. The fast rate of decomposition for food waste and paper caused the production of CO is favoured rather than H_2. Whereas yard waste with high moisture and low carbon content reduces the decomposition rate hence reduced the temperature, thus caused some produced CO and CH_4 were more prone to the reaction of water-gas shift and steam-methane reforming to produce H_2.

4. Conclusions

The CFD simulation analysis of sub-component in MSW including food waste, paper and yard using plasma downdraft gasification process is presented in this paper. The results showed that food waste and paper was typically produced higher content of CH_4 and CO as compared to yard waste. This were due to high content of C in food waste and high volatile matter content in paper that caused the rate of carbon decomposition increase. Whereas yard waste produced higher H_2 content compared to food waste and paper caused by the high amount of moisture content and low volatile matter which reduce the carbon decomposition. Thus, the gasification process is more prone to the reaction involving the production of H_2 rather than CO.

Acknowledgement
This research was supported by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS) (FRGS/1/2019/TK07/UTHM/03/2) and Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q030).

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