



Gasification of Municipal Solid Waste in Dual Reactor Fluidized Bed with Steam and CO₂ as Gasification Agent

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Abstract. Municipal solid waste (MSW), a prevalent environmental concern, presents a significant energy harnessing opportunity. This study explores the gasification of MSW into a usable gaseous fuel utilizing a Dual Reactor Fluidized Bed, a thermal technology that transitions solid substrates into gases. The primary objective of this gasification process is to generate a superior quality gas by employing specific gasifying agents, with a comparative analysis of steam and CO₂ against conventional air. This research particularly examines the influence of these agents on the H₂/CO ratio under varying operational temperatures, ranging from 400°C to 700°C. Employing silica sand as a medium for heat conduction between interconnected reactors, the investigation demonstrates that syngas composition is profoundly affected by fluctuations in gasification temperatures. A rise in temperature correlates with an enriched syngas composition, evidenced by heightened CO and H₂ levels when the temperature is elevated from 400°C to 700°C. Notably, the transition from air to steam as the gasification agent resulted in a substantial increase in H₂ concentration, reaching 28.6%. Conversely, utilizing CO₂ as the gasifying agent led to a surge in CO composition, with a peak value of 24.8%. The study further reveals a H₂/CO ratio augmentation from 0.6 with air to 1.3 with steam (H₂O), and 0.7 with CO₂, indicating the critical role of the gasifying agent. In conclusion, the findings underscore an overall enhancement in the heating value of the produced gas, attributable to both the escalation in gasification temperature and the transition among different agents (air, steam, and CO₂). This research illuminates the potential for optimizing syngas production from MSW, thereby turning a substantial environmental challenge into a promising energy solution.

Keywords: Gasification, Municipal solid waste, Dual reactor fluidized bed, Agent gasification, syngas.

1 INTRODUCTION

Municipal Solid Waste (MSW) emerges as a significant environmental challenge, particularly in urban locales, a byproduct of rapid economic development [1]. Projected data from the Indonesian Ministry of Environment and Forestry indicate an alarming

accumulation of waste, expected to crest at 16.6 million tons in 2021. This daunting figure comprises 58.8% organic and 41.2% inorganic waste, with only 71.49% undergoing proper management. Despite recycling, composting, and incineration for energy recovery, landfilling remains the predominant waste management strategy, especially in developing nations [2]. However, this approach is fraught with issues, including substantial greenhouse gas emissions [3], environmental degradation, and land scarcity, necessitating a shift toward sustainable waste-to-energy (WTE) alternatives.

The current energy landscape is heavily reliant on fossil fuels crude oil, coal, and natural gas [4]. The depletion of these resources, coupled with their environmental repercussions, necessitates exploring renewable energy sources, such as waste-derived energy. Thermochemical technologies, specifically combustion and gasification, are promising methods for converting waste biomass into energy. Gasification, in particular, transforms MSW into valuable gaseous fuels, including carbon monoxide (CO), hydrogen (H₂), and methane (CH₄), through a multi-stage process encompassing pyrolysis, partial combustion, and gasification of decomposition products. However, the conversion efficiency, particularly the H₂/CO ratio, remains suboptimal.

Previous studies have delved into various facets of MSW gasification. For instance, Saleh [5] utilized a downdraft gasifier and observed that elevated temperatures enhanced gas generation rates and constituent levels, influencing both Cold Gas Efficiency and Low Heating Value. Concurrently, Jamro, I.A., et al. conducted research using a tubular reactor, focusing on optimizing hydrogen production through temperature and heating rate modifications.

The choice of gasifying agent is pivotal in maximizing fuel-to-syngas conversion. Air, despite its accessibility, presents challenges due to its nitrogen content, diminishing the calorific value of the resultant gas. Alternative agents, like steam, offer potential benefits, reacting with char to produce nitrogen-free gas products. Investigations by Couto, Silva, Rouboa [6], and Xu et al. [7] have demonstrated the positive impact of steam gasification on MSW conversion efficiency, particularly at higher temperatures.

Furthermore, CO₂'s role as a gasifying agent merits consideration, especially in the context of carbon capture technologies. Studies by Pohořelý, M., et al., and Antolini, D., et al., [8, 9] have indicated that CO₂ injection can enhance char-to-gas conversion and specific energy parameters. Spiegl [10] also found that a combination of CO₂ and steam significantly affected gasification performance and the H₂/CO ratio.

This research introduces an innovative approach by employing a Dual Reactor Fluidized Bed (DRFB) for MSW gasification, separating the gasification and combustion zones to enhance gas quality. The DRFB, comprising two interconnected reactors, facilitates char and bed material flow. This study delves into the nuanced impacts of different gasification agents air, steam, and CO₂ on syngas characteristics, particularly the H₂/CO ratio, marking a significant stride toward sustainable, waste-derived energy solutions.

2 EXPERIMENTAL SETUP

The DRFB system employs two interconnected reactors: an endothermic gasifier and an exothermic combustion reactor, as depicted in the schematic presented in Figure

1. Constructed from SS 304 stainless steel, the reactors are designed to endure the high temperatures specified for these processes. The gasifier is relatively wider with a diameter of 152 mm, while the combustion reactor is narrower at 51 mm. The reactors' heights are set at 1000 mm and 1500 mm, respectively, tailored to their operational needs. Positioned at the upper end of the combustion reactor is a separator, also measuring 152 mm in diameter.

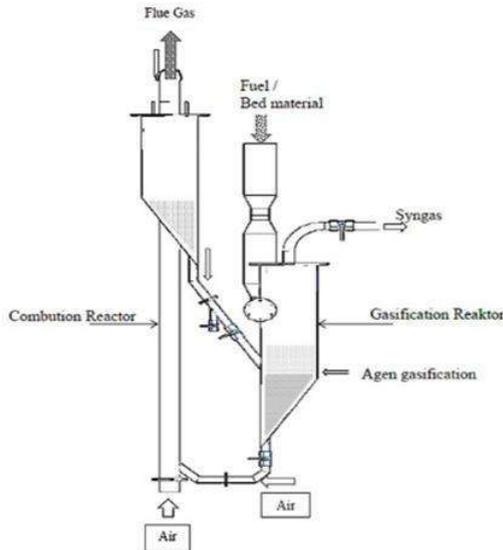


Fig. 1. The Schematic of dual reactor fluidized bed.

This separator plays a dual role: it effectively distinguishes solids from gases, and it aids in the circulation of solid materials back to the gasifier. The bed material, key in transferring heat from the combustion reactor, travels to the gasifier via the upper loop seal. Subsequently, the char, along with the bed material, is routed back to the burner through the lower loop seal, thereby maintaining a consistent thermal and material balance within the system.

The study employed experimental tests within Dual Reactor Fluidized Bed (DRFB) gasification reactors, introducing varying gasification agents directly into the surface of the bed material. Silica sand, with particle sizes ranging from 0.250 to 0.50 mm, was chosen as the bed material. The experiments were conducted under specific thermal conditions, with the gasification temperature maintained between 400-700 °C, and a consistent combustion reactor temperature of 700 °C. Municipal Solid Waste (MSW), sourced from a landfill in Denpasar, served as the fuel substrate. The fuel was systematically fed into the gasification reactor via a fuel feeder, operating at a rate of 0.3 m³/s and under atmospheric pressure conditions. Upon the introduction of a gasifying agent, the reactor facilitated a series of processes including gasification, pyrolysis, and drying, leading to the bubbling of the fluidized bed. To enable the circulation of char and bed material to the combustion reactor, air was propelled through the bottom loop seal.

3 RESULTS AND DISCUSSIONS

Both ultimate and proximate analyses were undertaken to evaluate the intrinsic properties and calorific potential of the selected fuel. The summarised data from these assessments is presented in Table 1. These preliminary examinations aimed to calibrate the experimental conditions for the ensuing tests. As delineated in Table 1, the MSW sample registered a moisture content of 6.73%, a volatile matter content of 56.57%, and a calorific value of 3065.937 cal/gram, thereby underscoring its suitability as a feasible fuel candidate for gasification. The proximate analysis was executed using the LECO TGA 701 instrument, adhering to the ASTM D7582 MVA Biomass method standards. Concurrently, the calorific value was ascertained using the Parr 1341 Plain Jacket Bomb Calorimeter, in strict accordance with the ASTM D240 methodology. In a complementary approach, an ultimate analysis was also performed on the MSW samples to quantify the content of key elements including carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). This analysis employed the LECO CHN628 series analyzer, abiding by the stipulations of the ASTM D5373 method for fuel analysis. The comprehensive outcomes of these investigative procedures are compiled and elucidated in Table 2.

Table 1. Proximate testing of MSW.

Material	Moisture (%)	Volatile (%)	Fixed Carbon (%)	Ash (%)	LHV (cal/gram)
MSW	6.73	56.57	14.24	22.45	3065.937

Table 2. Ultimate testing of MSW.

Material	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)	Oxygen (%)
MSW	64.46	11.50	0.52	0.05	18.03

As illustrated in Figure 2 (a, b, c), syngas composition demonstrates notable variability in response to operational temperature modifications throughout the gasification process. When air is utilized as the gasifying agent, the concentrations of CO, H₂, and CH₄ exhibit an upward trajectory correlating with temperature escalations. Specifically, within the 400°C to 700°C temperature spectrum, the content of CO elevates from 3.8% to 6.8%, H₂ content amplifies from 2.4% to 4.4%, and CH₄ content ascends from 1.2% to 1.7%. This trend can be attributed to the heightened interactions between the charcoal and the liquid constituents during gasification, propelling an increase in syngas volume yielded from the charcoal-gasification medium reactions, concurrent with a reduction in water content.

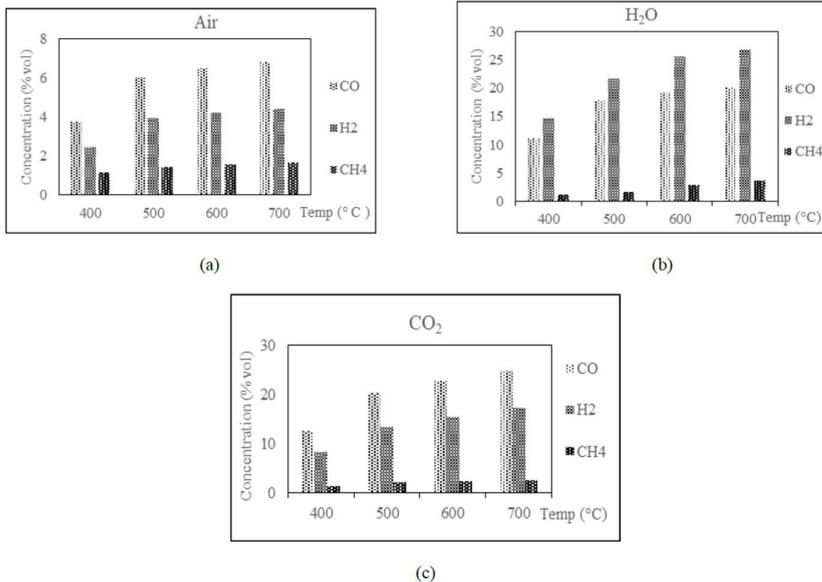


Fig. 2. Effect of temperature on syngas composition (a) Air as agent gasification, (b) H₂O as agent gasification, (c) CO₂ as agent gasification.

Conversely, employing steam as the gasifying medium, a temperature rise prompts the CO content to soar from 11.1% to 20.1% and H₂ from 14.7% to an impressive 26.8%, while CH₄ sees a modest increase from 1.3% to 3.7%. A similar uptrend in syngas composition is noticeable with CO₂ as the gasifying agent; CO jumps from 12.6% at 400°C to successive increments at higher temperatures, reaching 22.8% at 700°C. These trends result from the intensified reaction between the charcoal and the liquid phase within the gasification medium as temperatures climb, culminating in an expanded syngas volume [11, 12]. The diminished calorific value of producer gas derived from biomass gasification using air is a significant limitation, necessitating a higher biomass throughput, a considerable downside in this setting.

Figure 3 reveals the impact of different gasification agents on the resultant gas composition. CO concentration elevates from 6.8% to 20.1% and further to 24.8% when transitioning from air to steam, and finally to CO₂ as gasification agents. Similarly, H₂ undergoes a composition shift from 4.4% with air to 26.8% with steam and settles at 17.2% with CO₂. This corresponds with a decrease in nitrogen, CH₄, and CnHm fractions, instigating a chemical equilibrium shift in the gasification reaction and consequently a concentration increase in hydrogen and carbon monoxide [13]. Notably, the heating value of the resulting gas alters based on H₂ and CO concentrations. Air gasification produces the lowest heating value at 3.7 MJ/m³, CO₂ gasification stands at 8.6 MJ/m³, and H₂O gasification peaks at a substantial 11.9 MJ/m³. This enhanced calorific value is in direct proportion to the elevated levels of H₂ and CO generated by each respective gasification agent.

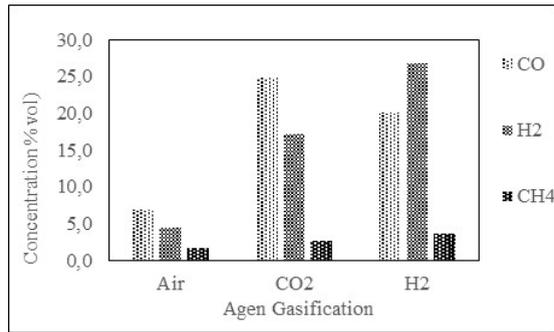


Fig. 3. Effect of air, H₂O, and CO₂ on syngas composition.

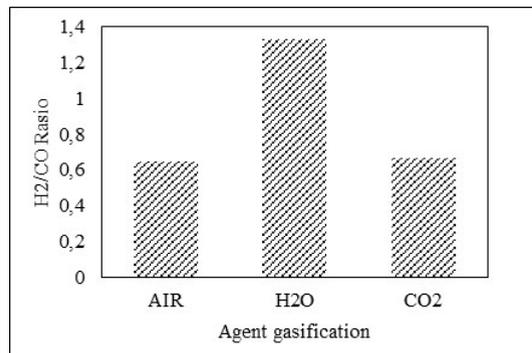


Fig. 4. Effect of air, H₂O, and CO₂ on H₂/CO ratio.

Figure 4 illustrates the impact of employing steam and CO₂ on the H₂/CO ratio during gasification. In the scenario of air gasification, the H₂/CO ratio is observed at 0.6. This figure experiences a significant rise to 1.3 when steam comes into play as the gasifying agent. Conversely, CO₂ gasification results in an H₂/CO ratio of approximately 0.7. The underlying chemical reactions during gasification explain these variations. When steam acts as the gasifying medium, it induces a reaction that disproportionately boosts the concentration of H₂ compared to CO. This phenomenon is attributable to the water-gas shift reaction, where steam reacts with carbon to produce a higher amount of hydrogen gas. In contrast, the utilization of CO₂ as the gasifying agent primarily increases the production of CO relative to H₂. This is due to the dry reforming process, where carbon dioxide reacts with carbon, resulting in a greater proportion of carbon monoxide. These insights underscore the critical influence of the choice of gasifying agent on the syngas composition, particularly the H₂/CO ratio, an essential parameter in assessing the syngas's potential applications and efficiency.

4 CONCLUSION

The research outcomes from the utilization of air, steam, and CO₂ as gasification agents in a Dual Reactor Fluidized Bed (DRFB) with Municipal Solid Waste (MSW) as fuel indicate that an elevation in gasification temperature propels an upsurge in gas production. This increment is attributed to the intensified gasification of carbon, leading to a diminished presence of charcoal in the residual byproducts of gasification. Employing air in the gasification process yields a relatively limited volume of syngas. This phenomenon is influenced by the oxygen component of the air, which contributes to a substantial concentration of CO₂ within the resultant gas. Additionally, the inherent nitrogen in the air translates to a notable N₂ presence in the produced gas, consequently diluting the syngas composition. Conversely, the application of steam as the gasifying agent demonstrates a capacity to curtail the proportions of CO₂ and N₂ in the end gas, facilitating a notable enhancement in both hydrogen (H₂) and carbon monoxide (CO) concentrations. This scenario also witnesses a consequential ascent in the H₂/CO ratio, underscoring the efficacy of steam in bolstering hydrogen production. The potential for CO₂ as a viable gasification agent emerges from its status as a product of combustion. Its introduction into the gasification process promotes a significant enrichment in the syngas concentration, especially regarding CO. However, it's noteworthy that the H₂/CO ratio affiliated with CO₂ utilization is inferior compared to that observed with steam, indicative of a lesser hydrogen yield relative to carbon monoxide. This analysis signifies the profound impact of the selected gasification agents on the composition and quality of the syngas produced, implicating crucial considerations for enhancing efficiency and sustainability in waste-to-energy conversion strategies.

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