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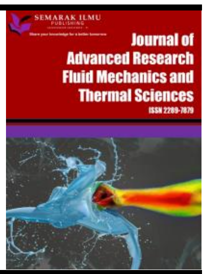

Optimizing Syngas Production from Municipal Solid Waste Gasification: A Dual Reactor Fluidized Bed Study with Steam and CO_2 as Gasification Agents

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ABSTRACT

The escalating production of municipal solid waste (MSW) poses significant environmental and health hazards due to air, water, and soil pollution. Utilizing MSW as an energy source through gasification offers a promising solution to mitigate these impacts. This study investigates the gasification of MSW using a Dual Reactor Fluidized Bed, a thermal technology that converts solid substrates into usable gaseous fuels. The primary objective is to optimize the quality of the produced syngas by employing specific gasification agents, namely steam and CO_2, and their mixtures. The research examines the effect of these agents on H_2/CO ratios across a wide range of low operating temperatures, from 400°C to 700°C, using silica sand as a heat conduction medium between interconnected combustion and gasification reactors. The results demonstrate that the composition of syngas is strongly influenced by gasification temperature fluctuations. Increasing temperatures from 400°C to 700°C correlate with higher concentrations of CO and H_2 in the syngas. The use of steam as a gasification agent yields H_2 concentrations up to 25%, while transitioning from steam to CO_2 leads to a substantial increase in CO composition, reaching 22.73%. Further analysis reveals that the H_2/CO ratio decreases from 1,78 with steam and 0.64 with CO_2, highlighting the crucial role of gasification agents in syngas quality. This study underscores the potential for optimizing syngas production from MSW by manipulating gasification temperatures and transitioning between different agents (steam, CO_2, and their mixtures), resulting in an overall increase in the calorific value of the produced gas. These findings emphasize the opportunity to transform substantial environmental challenges associated with MSW into promising sustainable energy solutions through advanced gasification technologies.

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1. Introduction

The global population growth, coupled with rapid economic and industrial development, has led to a significant increase in energy consumption and waste generation. It is estimated that by 2050, the world will produce 3.4 billion tons of waste annually [1]. The quantity and composition of waste are influenced by various factors, including economic conditions and socio-cultural aspects specific to each location [2]. Urban areas, particularly residential and industrial zones, are the primary sources of waste, such as solid waste, food residues, leaf litter, wood, paper products, and plastic. This waste production has resulted in air, water, and soil pollution, posing severe threats to the environment and human health. To address these waste-related issues and preserve the environment, technological advancements have led to the implementation of various waste management methods.

Interestingly, utilizing waste as an energy source could be a viable solution to meet the increasing energy demand caused by population growth and consumer consumption. Waste is abundant and easily accessible compared to fossil fuels or natural gas [3]. Municipal Solid Waste (MSW), which primarily consists of organic waste with high carbon content, has a high calorific value and contains useful gases, making it a promising source of energy [4]. However, many developing countries struggle with waste management issues due to inadequate utilization of advanced technologies, leading to challenges in collection, disposal, and incineration [5].

Among the various waste management methods, the landfill approach is the most widely used [6,7]. Although this method can capture up to 50% of the generated Methane gas for energy use, it has limitations in breaking down inorganic waste and takes around 30–60 days to produce Methane [8]. Moreover, the resulting leachate can pollute groundwater, while the gas, consisting of Methane and carbon dioxide, contributes to air pollution and exacerbates the greenhouse effect [9]. Additionally, the need for available land poses a challenge to this method.

Thermochemical processes, such as incineration and gasification, are often employed to convert waste into energy. Incineration involves the direct burning of MSW to generate heat, effectively reducing the volume of waste by 70% - 90% and minimizing the land required for disposal [10]. However, this process may produce pollutants like NOx and SOx, contributing to air pollution, ozone layer depletion, and global warming [11,12].

Gasification, on the other hand, is increasingly regarded as an eco-friendly and cost-effective waste-to-energy technique compared to incineration and landfill [13]. This process involves various stages, including drying, thermal decomposition, partial combustion of steam and charcoal, and gasification of products [14]. MSW gasification can effectively transform carbon-containing materials into a high-calorific gas product, known as syngas, which consists of Hydrogen (H_2), Carbon Monoxide (CO), Methane (CH_4), and other impurities [15]. Enhancing the oxidation and reduction reactions in the pyrolysis, oxidation, and reduction zones can greatly improve the conversion of charcoal into gas [16].

Recent studies have explored the use of different gasification agents, such as air, steam, or mixtures, to generate high-quality syngas [17,18]. Steam gasification in a fluidized bed gasifier has shown promise as a cost-effective method for managing MSW [19]. Additionally, the use of CO_2 as a gasification agent is expected to reduce the impact of CO_2 emissions on the environment by reacting with carbon and increasing char conversion, ultimately improving syngas quality [20-22].

This research explores the application of Dual Reactor Fluidized Bed (DRFB) technology of MSW gasification, offering a unique approach compared to traditional gasifiers. The DRFB system employs two separate reactors for combustion and gasification processes, which significantly reduces the presence of N_2 in the produced syngas. The combustion reactor utilizes a fast fluidized bed, while the gasification reactor operates with a bubbling fluidized bed. The study focuses on investigating the influence of various gasification agents, including steam, CO_2, and their combinations, on the quality of the syngas produced. By examining the effects of these agents on syngas composition and overall gasification efficiency, this research aims to contribute to the development of more advanced and sustainable waste-to-energy solutions. The outcomes of this study are anticipated to provide valuable insights into addressing the critical environmental and energy challenges faced by the global community, offering a promising pathway toward effective waste management and clean energy production.

2. Methodology

The experiments were conducted using a custom-designed Dual Reactor Fluidized Bed (DRFB) gasification system, developed and constructed at Udayana University. The DRFB consists of two interconnected reactors: a bubbling fluidized bed gasification reactor and a fast fluidized bed combustion reactor (Figure 1). The unique design of the DRFB allows for efficient heat transfer from the combustion reactor to the gasification reactor, facilitating the endothermic gasification reaction and enabling the effective conversion of feedstock into fuel. Both reactors were fabricated using high-quality stainless-steel pipes. The gasification reactor has a diameter of 152 mm and a height of 1000 mm, while the combustion reactor has a diameter of 51 mm and a height of 1500 mm. The reactors are connected by upper and lower loop seals (LS), which are constructed from stainless steel pipes with a diameter of 25.4 mm. The LS plays a crucial role in circulating the bed material and charcoal between the two reactors, ensuring the smooth and efficient operation of the DRFB.

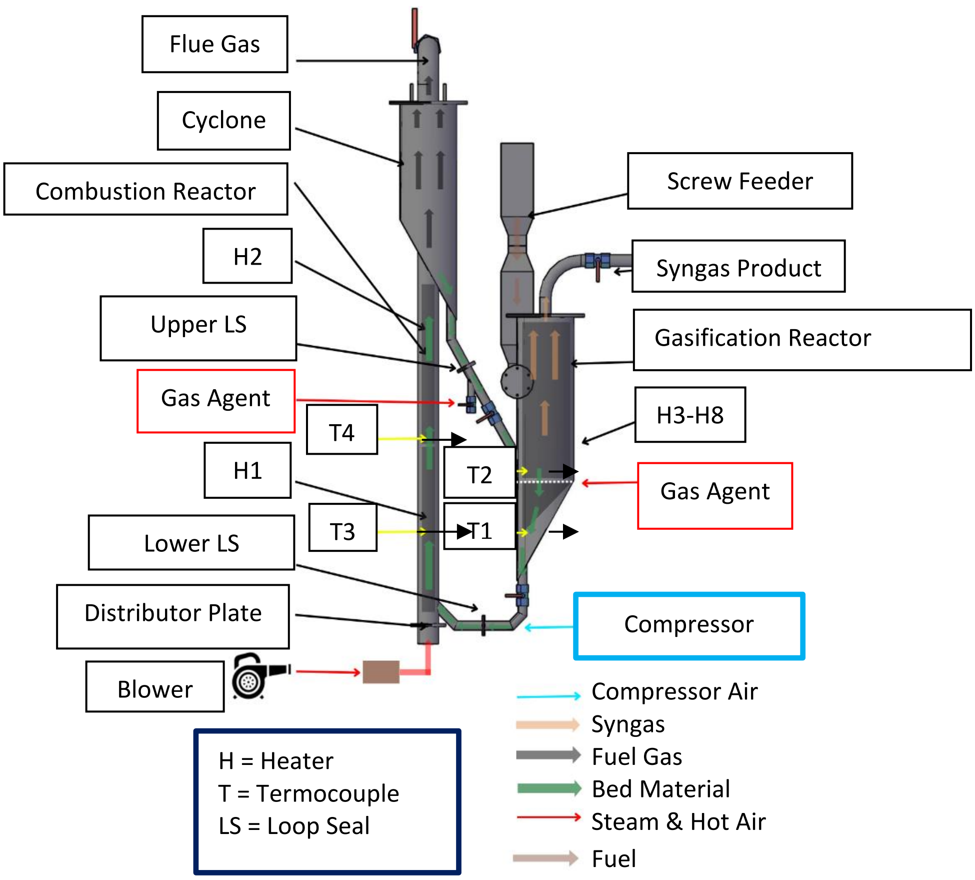

Fig. 1. Schematic test rig of DRFB reactor

The Lower LS is responsible for transferring the charcoal and bed material from the gasification reactor to the combustion reactor. In the combustion reactor, the charcoal undergoes combustion, generating the necessary heat for the gasification process. The upper LS carries the hot bed material from the combustion reactor back to the gasification reactor, where it heats the feedstock, promoting optimal fuel conversion efficiency. A screw-type fuel feeder is positioned at the top of the gasification reactor, allowing for the controlled introduction of the feedstock into the system. At the top of the combustion reactor, a separator with a diameter of 152 mm is installed to efficiently separate the flue gas from the solid residues generated during the combustion process.

The experimental procedure involves several steps. First, the DRFB is preheated to the desired operating temperature using an external heat source (H1 and H2 for the combustor, H3-H8 for the gasifier). The K-type thermocouple made from stainless steel is used to measure the temperature. This thermocouple has a temperature detection range of -200 °C to 1200 °C and an accuracy of 0.5 °C. A Graphtec GL240 data logger is employed to record experimental data from the beginning to the end of the experiment. The produced syngas is collected from the top of the gasification reactor, including CO, H_2, and CH_4, a synchronous type gas analyzer is used to continuously monitor their concentrations, while a Gasboard 3100P Syn Gas Analyzer is utilized to determine the composition of the resulting syngas.

To transfer heat from the combustion reactor to the gasification reactor, silica sand is utilized as a bed material. Silica sand has a mass of 2 kg, a size of 0.35-0.5 mm, a 2.196 gr/cm^3 density, and a melting point of 1713 °C. The gasification process begins with the continuous feeding of MSW into the gasifier via a screw feeder at a rate of 0.3 m^3 per minute. The gasification agents, such as steam and CO_2, are injected into the gasification reactor with a fuel agent ratio of 0.25 kg/kg of fuel. The agent gas injection occurs in the reduction zone, with a mixture ratio varying from 0% to 100%, as listed in Table 1.

Table 1
The variation of the mixture of steam and CO_2

Varied	Steam (%)	CO_2 (%)
I	100	0
II	75	25
III	50	50
IV	25	25
V	0	100

Fluidization is achieved by introducing hot air at a temperature of 300°C using a compressed air blower, assisted by a compressor, at the bottom loop seal. This process transports the remaining MSW char-coal and bed material into the fast-fluidized bed. The air is dispersed through a distributor plate located at the bottom of the combustion reactor at a velocity of 10 m/s to fluidize and circulate the bed material.

The MSW used in this study was obtained from one of the waste processing facilities located in Denpasar-Bali. Prior to analysis, the collected MSW was scratched and screened using 60-mesh and 30-mesh screen to ensure a uniform particle size distribution. A series of tests were conducted on the prepared MSW sample to determine its chemical composition and fuel properties. Proximate analysis was performed using a LECO TGA 701 device, following the ASTM D7582 MVA Biomass method. This analysis provided information on the mass levels of water, ash, volatile matter, and fixed carbon present in the MSW sample. The calorific test, which determines the heating value of the fuel, was carried out using a Parr 1341 Plain Jacket Bomb Calorimeter in accordance with the ASTM D240 method.

Ultimate analysis was conducted to quantify the elemental composition of the MSW sample, including Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), and Sulfur (S) content. This analysis was performed using a LECO CHN6 28 analyzer and followed the ASTM D5373 Fuel Analysis method. The results of both the proximate and ultimate analyses of the MSW sample are presented in detail in Table 2.

Table 2
Proximate and ultimate test of MSW

Proximate Analysis (%)	Ultimate Analysis (%)
Moisture 6.73	C 64.6
Volatile 56.57	H 11.50
Fixed Carbon 14.24	O 18.03
Ash 22.45	N 0.52
LHV (cal/gr) 3065.937	S 0.05

3. Results
3.1 The Effect of Temperatures

The effect of temperature on syngas composition is presented in Figure 2, illustrating the temperature variation between 400-700 °C at an agent fuel ratio of 0.25. The study investigated the impact of temperature on different gasification agents, including steam, CO_2, and a mixture of both. Figure 2(a) demonstrates that when using steam, the concentration of H_2 increased from 7.91% at 400 °C to 13.28% at 500 °C, 21.86% at 600 °C, and 24.99% at 700 °C. Similarly, the CO concentration increased from 1.28% at 400 °C to 6.98% at 500 °C, 12.84% at 600 °C, and 13.51% at 700 °C. Methane (CH_4) concentrations remained relatively stable at 2.27% between 500 °C and 700 °C.

The use of CO_2 as a gasification agent is influenced by the increase in temperature, which subsequently affects the composition of the syngas. As shown in Figure 2(b), when 100% CO_2 is used, the composition of CO reaches its highest level, increasing from 6.67% at 400°C to 22.93% at 700 °C. Likewise, the composition of H_2 also increases from 3.28% at 400 °C to 14.46% at 700 °C.

When using mixed agents (steam-CO_2), as depicted in Figure 2(c), with a composition of 50% steam and 50% CO_2, the CO composition increased from 3.86% at 400 °C to 8.27% at 500 °C, 15.96% at 600 °C, and 17.10% at 700 °C. The H_2 composition also increased from 4.61% at 400 °C to 18.72% at 700 °C, while CH_4 increased from 2% at 400 °C to 3.22% at high temperatures. However, CH_4 remains stable at low temperatures but decreases with increasing temperature, particularly between 600 °C and 700 °C. The concentration of Methane decreases as temperature is raised due to the enhancement of hydrocarbon reforming reactions.

The gasification process is a highly complex sequence of reactions influenced by various thermodynamic and kinetic factors. The composition of the syngas produced by the gasifier is the result of this reaction sequence. Temperature plays a crucial role in the reaction, as it enhances reaction speed and efficiency, enabling the conversion of MSW into high-quality syngas. At low temperatures (400 °C – 500 °C), the reaction and the percentage of volatiles released from MSW are minimal, resulting in a low production of syngas compared to temperatures above 600 °C. At high temperatures, thermodynamic gasification reactions are more favorable, and the equilibrium concentrations of various syngas species can be altered by temperature changes. Higher temperatures result in faster and more efficient reactions, leading to the conversion of more MSW into syngas with better quality, as evidenced by higher concentrations of H_2 and CO in the syngas.

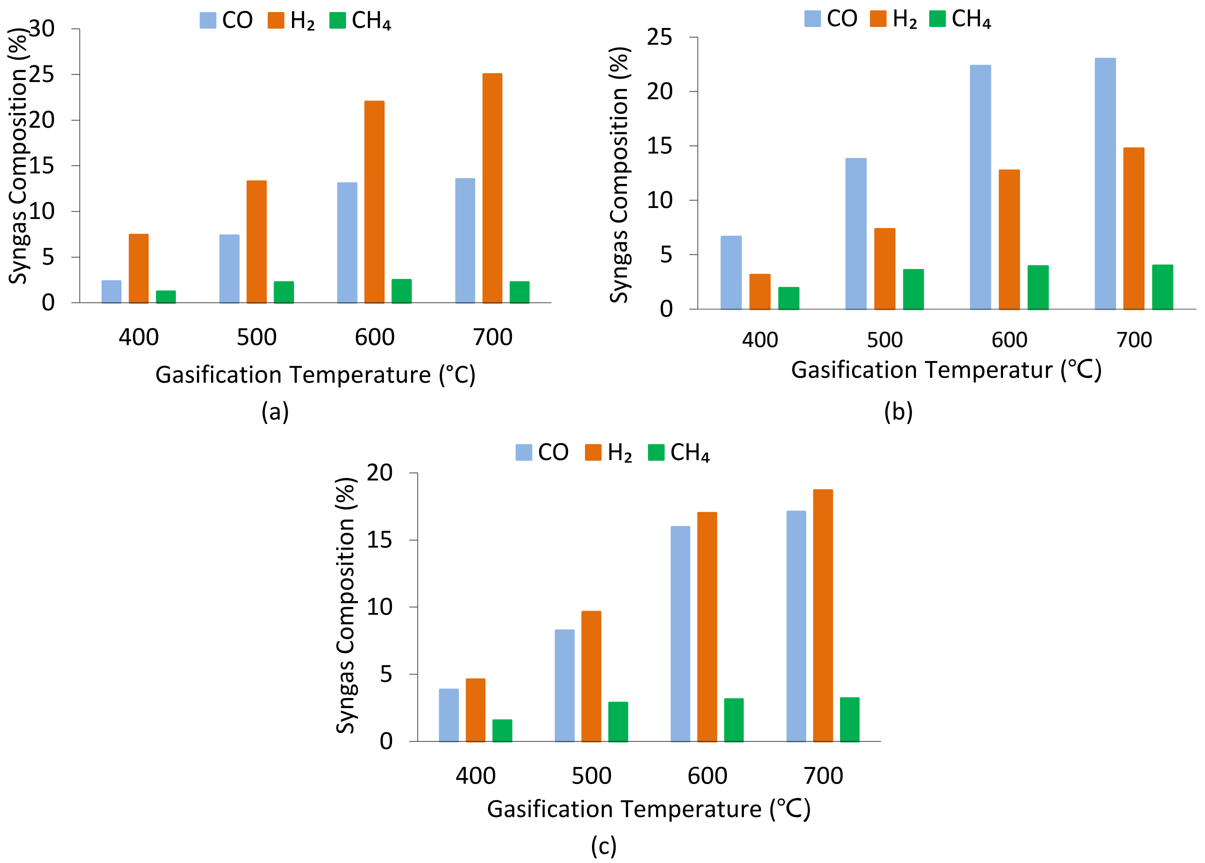

Fig. 2. Effect of temperature on syngas composition (a) 100% steam - 0% CO_2 (b) 0% steam - 100% CO_2 (c) 50% steam - 50% CO_2

The endothermic equilibrium reaction is temperature-dependent and intensifies with an increase in temperature. The steam, dry reformation, and syngas-concentration-boosting reactions are the key temperature-dependent reactions involved in the gasification process. The gasification process begins with drying MSW biomass, followed by thermal degradation or pyrolysis, which produces gases. Pyrolysis significantly impacts the entire gasification process, and temperature is the most critical factor in this regard. At higher temperatures, more MSW carbon is converted into volatiles via pyrolysis, resulting in a greater gas output. Therefore, temperature has a direct influence on the gasification process. By optimizing the temperature, the gasification process can be made more efficient, and the quality of the syngas produced can be improved.

When steam is used as a gasification agent, the water gas shift reaction becomes more dominant with an increase in temperature. This reaction contributes to the formation of syngas by converting CO and steam to H_2 and CO_2. On the other hand, the use of CO_2 as a gasification agent leads to an increase in the production of CO due to its reaction with coal through Boudouard's reaction at high temperatures. Additionally, at higher temperatures, CO_2 can also react with dry hydrocarbons, forming H_2 and CO [23]. CO_2 can be used as a gasification agent along with steam, which could help minimize the negative impact of CO_2 emissions on the environment. The use of CO_2 in the gasification process can also improve the quality of syngas by enhancing char conversion through chemical reactions with carbon.

3.2 The Effect of Varies Agent

To investigate the influence of gasification agents on syngas composition, a temperature of 700°C was selected. The agents employed for gasification were steam, CO_2, and a mixture of both. Figure 3 illustrates the composition of the gases produced using different gasification agents. When only steam is used as a gasification agent, the concentration of H_2 is higher compared to CO and CH_4. These findings suggest that a carbon conversion reaction occurs with steam, leading to the formation of H_2. The addition of steam has significantly influenced the reaction and increased the concentration of H_2 in the syngas.

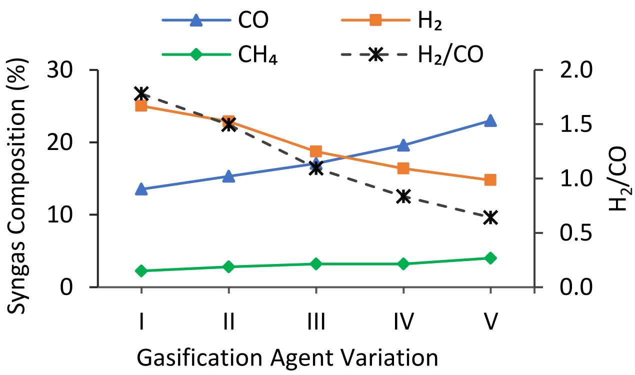

Fig. 3. Variation of gasification agent of Steam-CO_2 on syngas and H_2/CO

The process of substituting CO_2 for steam in the fluidizing gas is demonstrated by reducing the percentage of steam in the gasifier and mixing it with CO_2. The concentration of the mixture of steam and CO_2 is varied as shown in Table 2. As the concentration of CO_2 increases, the amount of H_2 continues to decrease from 23.73%, 21.74%, 18.12%, 15.21%, and 13.73%. The results from the mixture of steam and CO_2 indicate that CO_2 promotes the formation of CO, while steam enhances the production of H_2. The Water Gas Shift (WGS) reaction is responsible for higher H_2 concentrations and lower CO concentrations in certain conditions of the mixtures. The composition of CO increased from 6.8% to 16.76%, 19.69%, and 22.73% when CO_2 replaced steam as a gasification agent. This change is attributed to the variation in CH_4 composition, which causes a shift in the chemical equilibrium of the gasification reaction and an increase in the concentration of CO. The Boudouard reaction, which involves the reaction between coal and CO2, also contributes to the increase in CO.

As the amount of steam in the mixture decreases and the concentration of CO_2 increases, the H_2/CO ratio decreases. This ratio is crucial in industrial processes such as the Fisher-Tropsch Synthesis (FTS), which converts syngas (a mixture of CO and H_2) into fuels and chemicals. The H_2/CO ratio determines the selectivity and efficiency of this process. When only steam is used, the H_2/CO ratio is 1.78. However, when 100% CO_2 is used instead of steam, the CO composition reaches its highest level, leading to a decrease in the H_2/CO ratio to 0.60. This trend occurs because the formation of H_2 decreases while the formation of CO increases. The same reaction that causes an increase in CO composition was also observed in a study by Pinto *et al.,* [24].

The findings of this study highlight the significant impact of gasification agents on the composition of syngas produced from MSW. The choice of gasification agent, whether steam, CO_2, or a mixture of both, can be tailored to achieve the desired H_2/CO ratio, which is essential for specific downstream applications. The use of steam promotes the formation of H_2, while CO_2 favors the production of CO. By adjusting the ratio of these agents, the syngas composition can be optimized to meet the requirements of various industrial processes, such as the Fisher-Tropsch Synthesis. These results provide valuable insights into the potential of MSW gasification as a sustainable and efficient approach to waste management and energy production.

The change in syngas composition resulting from the use of different gasification agents directly influences the calorific value of the produced gas. The calorific value, also known as the Lower Heating Value (LHV), is a crucial parameter for assessing the efficiency of the gasification process. Figure 4 illustrates the effect of gasification agents on the calorific value of syngas. When steam is used as the sole gasification agent, the calorific value of the resulting syngas is 7.17 MJ/m^3, and increases to 7.64 MJ/m^3, to 8.11 MJ/m^3, to 8.58 MJ/m^3, when steam is mixed with CO2. In contrast, when only CO_2 is employed as the gasification agent, the calorific value of the syngas increases to 9.04 MJ/m^3. These variations in LHV are directly related to the changes in the composition of the syngas.

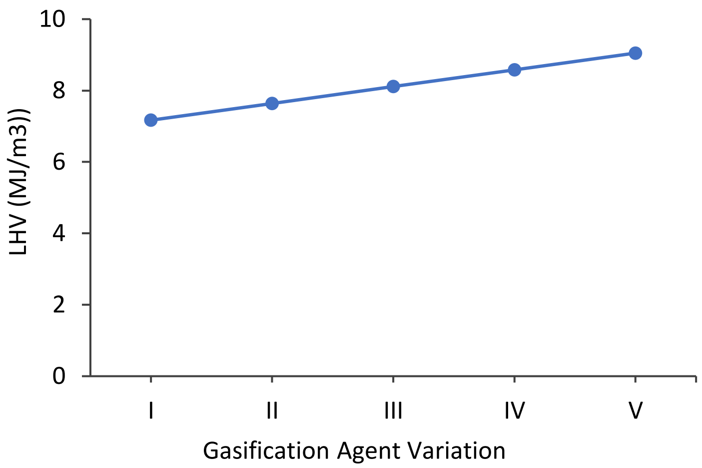

Fig. 4. Influence of various compositions of steam-CO_2 on LHV

The increase in the calorific value of the gases produced is associated with the rise in the concentrations of H_2 and CO, which are generated by using the respective gasification agents. H_2 and CO are the primary components that contribute to the energy content of the syngas. As discussed earlier, the use of steam as a gasification agent promotes the formation of H_2 through the water-gas shift reaction, while CO_2 favors the production of CO via the Boudouard reaction. The reaction is endothermic, it requires heat when C from the MSW reacts with CO_2 to produce CO. The elevated CO content enhances the calorific value of the syngas. The higher the concentrations of these energy-rich components in the syngas, the greater the calorific value of the gas and the overall efficiency of the process, leading to a higher.

Furthermore, the MSW feedstock also plays a role in determining the composition and quality of the gaseous products formed during gasification. Its elemental composition (C, H, O, N, S), moisture content, volatile matter, ash content, and contaminants contribute to the formation of CO, H_2, and CH_4 during gasification. The high carbon content and high volatiles have transformed their co-gasification into an attractive option to produce high caloric value syngas. Hydrogen contributes to the production H_2. Oxygen content can influence the formation of CO and CO_2. Oxygen also affects the overall stoichiometry of the gasification reactions. Oxygen also increases the gasification temperature due to the exothermic nature of oxidation reactions. This increase in temperature can enhance the efficiency and effectiveness of the gasification process, which in turn affects the LHV of the syngas.

The findings of this study highlight the importance of selecting the appropriate gasification agent to optimize the calorific value of the syngas produced from MSW. By employing CO_2 as a gasification agent, the LHV of the syngas can be significantly increased compared to using steam alone. This increase in calorific value has direct implications for the downstream utilization of the syngas, such as in power generation or as a feedstock for chemical synthesis processes. The higher the calorific value of the syngas, the more efficient and economically viable these applications become.

Moreover, the use of CO_2 as a gasification agent not only enhances the calorific value of the syngas but also offers environmental benefits. By utilizing CO_2, which is a greenhouse gas, in the gasification process, its emission into the atmosphere can be mitigated. This approach aligns with the principles of carbon capture and utilization (CCU), where CO_2 is converted into valuable products instead of being released into the environment. Thus, the gasification of MSW using CO_2 as a gasification agent presents a promising strategy for sustainable waste management and energy production while simultaneously addressing the challenges of greenhouse gas emissions.

4. Conclusions

This study demonstrates the potential of municipal solid waste (MSW) gasification using a Dual Reactor Fluidized Bed (DRFB) reactor as a promising solution for sustainable waste management and energy production. The findings highlight the significant influence of gasification temperature and agents on the composition and calorific value of the produced syngas. The results show that increasing the temperature from 400 °C to 700 °C leads to a substantial increase in CO and H_2 levels, with H_2 concentration reaching up to 25% when steam is used as the gasification agent. Transitioning from steam to CO_2 as the gasification agent results in a remarkable increase in CO composition, reaching 22.73%. Furthermore, the study reveals a decrease in the H_2/CO ratio from 1,78 with steam to 1.09 with a mixture of steam and CO_2, and 0.64 with CO_2, underlining the crucial role of gasification agents in determining syngas quality. These findings emphasize the overall increase in the calorific value of the produced gas, driven by the escalation of gasification temperatures and the strategic use of different agents. By optimizing these parameters, the DRFB system can efficiently convert MSW into high-quality syngas, offering a viable pathway to address environmental challenges while harnessing the energy potential of waste.

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