Applied Chemical Engineering (2024) Volume 7 Issue 1
doi: 10.24294/ace.v7i1.2459

ORIGINAL RESEARCH ARTICLE

Innovative downdraft gasifier design utilizing exhaust gas as gasification agent for sustainable syngas production

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ABSTRACT

This study introduces an innovative downdraft gasifier design that harnesses exhaust gas as the gasification agent, showcasing successful operation and extensive experimental investigations using various biomass feedstocks, notably wood pellets of different sizes (<20 mm to 20–50 mm). The gasification system exhibited the ability to produce clean syngas suitable for both heating and electricity generation. Experimental assessments encompassed a temperature range of (620 to 1250 ℃) and an equivalence ratio range of 0.2 to 0.5. The resulting syngas composition featured key constituents such as H_2, CO, CO_2, and CH_4, consistent with conventional gasification processes. The incorporation of exhaust gas as the gasification agent represents a pioneering advancement. This innovative approach not only minimizes energy input but also reduces greenhouse gas emissions, rendering the system more environmentally sustainable. The flow rate of the primary gasification agent was measured at 440 m^3/h, and the producer gas's exit temperature (300–650 ℃) was analyzed based on the moisture content of the biomass feedstock. The temperature within the reaction zone varied depending on the equivalence ratio (ER) for exhaust gas (700–974 ℃) and for air (ranging from 620–850 ℃). Additionally, the temperature was influenced by the moisture content, with ranges of (830–1050 ℃) for exhaust gas and 850–1050 ℃ for air. The syngas produced consisted mainly of carbon monoxide (14.4%–19.2%), hydrogen (16%–20%), carbon dioxide (7.1%–11.2%), and a small amount of methane (2%–3%). This innovative downdraft gasifier design holds substantial promise as a renewable energy system, particularly due to its utilization of low-cost materials and reduced environmental footprint. Such advancements pave the way for the widespread adoption of downdraft gasifiers, making them an attractive technology for thermal and power applications, especially in developing nations.

Keywords: biomass; gasification; downdraft gasifier design; exhaust gas; producer gas; power generation

ARTICLE INFO

Received: 20 July 2023
Accepted: 25 September 2023
Available online: 15 December 2023

1. Introduction

In the face of escalating global energy demands and the urgent need to combat climate change, the pursuit of sustainable and renewable energy sources has gained paramount significance. The reliance on fossil fuels, historically the backbone of our energy infrastructure, has been linked to detrimental environmental impacts, primarily the emission of greenhouse gases (GHGs) like carbon dioxide (CO_2). Transitioning towards sustainable alternatives is essential to reduce these environmental consequences and secure a reliable energy supply for future generations. Sustainable and renewable energy sources are crucial for addressing these challenges.

These sources, including solar, wind, hydropower, and bioenergy, offer the promise of a low-carbon energy future that minimizes environmental harm. They are essential in mitigating the effects of climate change and ensuring energy security. Achieving a sustainable energy mix is vital not only for reducing GHG emissions but also for enhancing energy resilience and independence[1–3].

Now, let's expand on the importance of both sustainable energy and gasification technology, as well as the significance of gasification-related terminology in the context of energy exploration:

- Addressing climate change: Sustainable energy, including renewables like wind, solar, and hydropower, is a critical tool in combatting climate change. By reducing greenhouse gas emissions, these sources help mitigate the warming of our planet. Gasification technology can complement this effort by converting a wide range of feedstocks, including carbon-neutral biomass, into clean energy, further reducing carbon footprints[4].
- Energy security: Sustainable energy sources contribute to energy security by diversifying the energy mix. Gasification, with its flexibility to use various feedstocks, enhances this diversification, reducing reliance on fossil fuels and their associated geopolitical vulnerabilities[5].
- Resource conservation: Sustainable energy taps into renewable resources, preserving finite fossil fuel reserves for future generations. Gasification plays a role by making more efficient use of resources, such as converting waste into energy, thereby reducing environmental pressures[6].
- Economic growth: Investment in sustainable energy technologies stimulates economic growth. It creates jobs in the renewable energy sector and fosters innovation in gasification, driving economic benefits at both local and global scales[7].
- Energy access: Sustainable energy technologies are instrumental in extending energy access to underserved populations. Gasification can provide decentralized energy solutions, improving the quality of life for those without access to traditional energy grids[8].
- Resilience to energy shocks: Both sustainable energy and gasification technologies contribute to energy resilience. Sustainable sources are less vulnerable to supply disruptions, while gasification can help manage energy demand during crises[9].
- Technological advancements: Sustainable energy research drives technological advancements in energy storage, grid integration, and efficiency. Gasification-related terminology is essential for describing and sharing these innovations[10].
- Waste reduction: Gasification can convert waste materials, including plastics and organic matter, into valuable energy and products. This contributes to waste reduction, lowers landfill use, and minimizes environmental contamination[11].
- Circular economy: Gasification is a key component of the circular economy, as it transforms waste and byproducts into resources, reducing the linear consumption of raw materials and promoting sustainability[12].

Within the realm of renewable energy technologies, gasification stands out as a pivotal enabler. Gasification technology provides a versatile and efficient means of converting a diverse range of feedstocks, including biomass, agricultural residues, and waste materials, into valuable synthesis gas (syngas)[13]. Syngas, consisting primarily of hydrogen (H_2) and carbon monoxide (CO), is a flexible energy carrier with applications in electricity generation, heat production, and biofuel synthesis[14]. Gasification's significance lies in its capacity to extract energy from feedstocks that would otherwise remain underutilized or discarded, thus promoting resource efficiency. Furthermore, gasification processes typically result in fewer emissions compared to direct combustion, contributing to cleaner energy production[15].

Downdraft gasifiers represent a significant advancement in gasification technology. These systems are known for their ability to produce high-quality syngas with reduced tar content and improved efficiency. The literature surrounding downdraft gasifier design and development is extensive, encompassing various aspects, including reactor configurations, feedstock compatibility, and operational parameters. These studies have provided valuable insights into the optimization of downdraft gasifiers for different applications and feedstock types[16,17].

In light of this context, the central hypothesis of this study posits that an innovative downdraft gasifier design, utilizing exhaust gas as the gasification agent, can significantly enhance energy efficiency and reduce greenhouse gas emissions, making it a promising technology for sustainable energy production. To test this hypothesis, the primary objective of this research is to conduct a comprehensive investigation into the operation and performance of the proposed downdraft gasification system. This study will encompass a series of experiments utilizing various biomass feedstocks, explore a wide range of temperature and equivalence ratio conditions, and analyze the composition of the resulting syngas. Through these investigations, we aim to validate the hypothesis and provide novel insights into the potential of this innovative gasifier design in advancing sustainable and renewable energy solutions in a rapidly evolving energy landscape.

2. Materials and methods

2.1. Feedstock preparation and analysis

The wooden material was taken from a company specialized in this type of industry establish at 10th of Ramadan city, Egypt. The analysis provided due to company labs. Proximate analysis is a technique used to determine the physical and chemical properties of a material by measuring the amount of moisture, ash, volatile matter, and fixed carbon present in a sample. This information is important for assessing the combustion behavior of wood, as well as its energy content. The proximate analysis of wood typically shows that it contains a significant amount of volatile matter, which contributes to its combustibility, as well as a relatively low amount of ash. **Table 1** illustrates that the proximate analysis provides information on the amount of moisture, ash, volatile matter, and fixed carbon present in the wood. In this sample, the wood has a moisture content of 10%, an ash content of 1%, a volatile matter content of 80%, and a fixed carbon content of 9%.

Table 1. Proximate analysis and ultimate analysis.

Proximate analysis		**Ultimate analysis**	
Moisture content (%)	10	Carbon (%)	50
Ash content (%)	1	Hydrogen (%)	6
Volatile matter (%)	80	Nitrogen (%)	0.5
Fixed carbon (%)	9	Sulfur (%)	0.1
		Oxygen (%)	43.4

Ultimate analysis is a technique used to determine the elemental composition of a material. It involves analyzing a sample for the percentage of carbon, hydrogen, nitrogen, sulfur, and oxygen by weight. This information can be used to calculate the heating value of the wood, which is an important parameter for assessing its suitability as a fuel. The ultimate analysis of wood typically shows that it is primarily composed of carbon, hydrogen, and oxygen, with smaller amounts of nitrogen and sulfur. **Table 1** shows the ultimate analysis provides information on the percentage of each elemental component in the wood. In this example, the wood has a carbon content of 50%, a hydrogen content of 6%, a nitrogen content of 0.5%, a sulfur content of 0.1%, and an oxygen content of 43.4%.

2.2. Gasifier design calculations

Gasifier calculations can be complex and depend on several variables, such as the type of gasifier, the fuel being used, and the desired output. However, here are some basic equations that can be used for simple gasifier calculations.

Table 2 shows the gasifier mathematical formula calculations[18–20]:

Table 2. Gasifier mathematical formula calculations.

Gasifier mathematical formula calculations		
Fuel consumption rate (*FCR*)	$FCR = \frac{Q_{net}}{CV \times \eta g}$	(1)
Specific gasification ratio (hearth load) (G_H)	$G_H = \frac{V°}{A_{th}}$	(2)
Producer gas flow rate	$V° = FCR \times C$	(3)
Diameter of throat	$d_{th} = \sqrt{\frac{1.27 \times V°}{G_H}} = \sqrt{\frac{3.175 \times FCR}{G_H}}$	(4)
Specific gasification rate (G_h)	$G_h = \frac{FCR}{A_R}$	(5)
Reactor diameter (D)	$D = \sqrt{\frac{4 \times FCR}{\pi \times G_h}} = \sqrt{\frac{1.27 \times FCR}{G_h}}$	(6)
Reactor height (*H*)	$H = \frac{G_h \times t}{\rho_b} = \frac{FCR \times t}{A_R \times \rho_b} = D + 1\frac{1}{2}D$	(7)
Agent flow rate (*AFR*)	$AFR = \frac{ER \times FCR \times [A/F]_s}{\rho_{agent}}$	(8)
Superficial air velocity (*Vs*)	$V_s = \frac{4 \times AFR}{\pi \times D^2} = \frac{1.27 \times AFR}{D^2}$	(9)
Diameter of the tuyer (d_t)	$d_t = \sqrt{\frac{4 \times AFR}{\pi \times v \times N_t}} = \sqrt{\frac{1.27 \times AFR}{v \times N_t}}$	(10)
Diameter of pyrolysis zone (d_c)	$d_c = 3.5\, d_{th}$	(11)
Height of inclination zone (H_i)	$H_i = \frac{1}{2}(d_c - d_{th})\tan\alpha$	(12)
Height of drying zone (H_d)	$H_d = \frac{FCR}{\rho_{bulk} \times A_p}$	(13)
Height of reduction zone (H_r)	$H_r = 1.2\, d_{th}$	(14)
Height of charging zone (H_c)	$H_c = \frac{8 \times FCR}{\rho_{bulk} \times \pi(0.001 d_c)^2}$	(15)
Gasifier efficiency	$\eta_g = \frac{CV_g \times V_g}{H_g \times FCR}$	(16)
Gasifier efficiency if syngas is used for direct burning works	$\eta_g = \frac{(CV_g \times V_g) + (V_g \times \rho_g \times C_p \times \Delta T)}{H_g \times FCR}$	(17)

Where C is a constant which considering one kilogram of biomass produces around 2.4 to 2.5 m^3 of gas, H_g is a lower heating value (LHV) of syngas, $(A/F)_s$ is the stoichiometry air-fuel ratio, ρ_{agent} is the agent density, v is the velocity of air inlet in tuyer (m/s) and N_t is the number of tuyer.

Downdraft gasifiers are known for their high cold gas efficiency, typically achieving efficiencies of 60%–80%. This is because the downdraft design allows for efficient combustion of the fuel, with the gases flowing downward through a bed of hot charcoal, where they are further heated and undergo additional chemical reactions. The result is a clean-burning gas that can be used for a variety of applications, including heat and power generation.

Gasifier design consideration:

- Reactor: throat type, made of stainless steel (AISI 310 S) 3 mm thickness, a diameter of 1380 mm, a total height of 3400 mm, a throat diameter of 320 mm, a throat height of 230 mm, gasifier has air jacket outside oxidation zone; producer gas passing through this jacket for preheating a gasification air. Air supply system; blower (2 kW) with capacity of 500 m^3/h, 30-unit nozzles (diameter of 18 mm), nozzle placed 614 mm above the grate. These nozzles were connected to the square shape primary gasification agent inlet manifold placed around the middle cylinder. The manifold was constructed from 100 × 50 × 4 mm rectangle mild steel pipes. Feeding system: hopper, feeding flow rate of 300 kg/h.
- Feeding system; in order to continues operation, fuel hopper is used for feedstock feeder and it is attached on the top of the gasifier. During gasification, the feedstock from hopper dropped to the gasifier reactor. The feeding unit used a screw, feeding rate depends on rotation speed of the drive motor.
- Temperature: measured by thermocouples (K type) with an accuracy of (0.75%; uncertainty arising from operation is 1.5%). Consequently, the total uncertainty in the temperature measurement T is estimated to be (1.68%).
- Air flow rate: measured by a rotameter with a full-scale of 1500 NL min^{-1} and a least count of 1000 NL min^{-1} and a specified accuracy of (10%).
- Gas composition analysis: measured by a gas chromatographer with an accuracy of (2%; a rather high uncertainty is estimated to be 5% caused by the manual procedure of sampling and injection).

Figure 1 shows the gasifier design of a downdraft gasifier that is used in the thesis experiments.

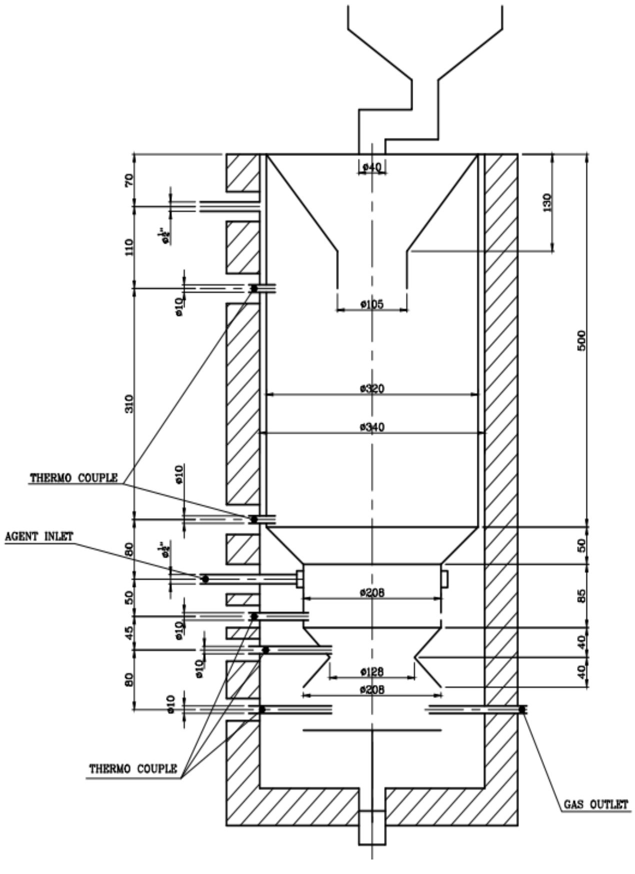


Figure 1. Gasifier design (dimensions in mm).

2.3. Process technology

The combustible substance of a solid fuel is typically comprised of elements oxygen, hydrogen and carbon. The syngas is formed by the partial combustion of solid biomass in the gasifier reactor. In the conventional theory of syngas, gasification reaction occurs in four zones which are oxidation, reduction, pyrolysis and distillation zones. The Gasification process technology is based on production of a highly combustible gas by controlled reactions of wood pellet biomass with gasification agent (air or exhaust gas). The most important homogeneous gas phase reactions and heterogeneous reactions between solid matter and gases are in the **Table 3**[21,22].

Table 3. Main process reactions

Reactions		**rH_0 (kJ/mol)**	**Remarks**
Pyrolysis Fuel + Heat → Gas (C_2H_4, C_nH_m, CO, CO_2, H_2, H_2O, etc.) + Tars + Char	(1)	-	-
Combustion		-	-
$C(s) + O_2 \leftrightarrow CO_2$	(2)	−394	-
$C(s) + 1/2\ O_2 \leftrightarrow CO$	(3)	−111	-
$CO + 1/2\ O_2 \leftrightarrow CO_2$	(4)	−283	-
$H_2 + 1/2\ O_2 \leftrightarrow H_2O$	(5)	−242	-
Gasification Homogeneous gasification reactions		-	-
$CO + H_2O \leftrightarrow CO_2 + H_2$	(6)	−41	Water gas shift reaction
$CH_4 + H_2O \leftrightarrow CO + 3H_2$ $C_nH_m + nH_2O \leftrightarrow nCO + (n + m/2)H_2$	(7)	+206	-
$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ $C_nH_m + nCO_2 \leftrightarrow 2nCO + (m/2)H_2$	(8)	+247	Dry (CO_2) reforming
Heterogeneous gasification reactions		-	-
$C(s) + CO_2 \leftrightarrow 2CO$	(9)	+172	Boudouard reaction
$C(s) + H_2O \leftrightarrow CO + H_2$	(10)	+131	Water gas reaction
$C(s) + 2H_2 \leftrightarrow CH_4$	(11)	−75	Methanation

Oxidation zone, the oxygen in the gasification agent reacts with the carbon and hydrogen in the fuel to reduce carbon and hydrogen to form carbon dioxide and water. Reduction Zone, the partial combustion products CO_2, H_2O gotten from oxidation zone are presently passed through reduction zone. Here CO_2 and H_2O are diminished to create carbon monoxide (CO) and hydrogen (H_2) by retaining heat from the oxidation zone[23]. Oxidation zone raise the temperature of reduction zone to advance the carbon/steam gasification response which has higher actuation energy. This reaction requires temperature of 900 °C and above. Over 90% of CO_2 is reduced to CO at temperatures above 900 °C. It is an endothermic reaction. The product gas principally contains the combustible gases (CO, H_2, CH_4) and also the incombustible gases (H_2O_{vapor}, CO_2, N_2) yet as variety of undesired trace compounds are present within the product gas. The factors affecting on the composition of the product gas are the types and composition of the biomass, form of gasification reactor and residence time, gasification temperature and pressure, presence of catalysts, sort and quantity of gasification agent, and several and several other factors.

3. Results and discussion

This research focuses on converting biomass waste into chemicals and energy. Thermochemical decomposition using both the microwave's energy conversion mechanism and the conventional superficial heat transfer techniques. The first step was to use conventional heating to undertake the gasification of agriculture residences on a small scale. after that, a chapter to explore microwave-assisted biochemical synthesis from biomass residue was demonstrated.

3.1. Equivalence ratio calculation

In the context of gasification, equivalence ratio is a term used to describe the ratio of the actual amount of air or oxygen present in the gasification process to the amount of air or oxygen that is theoretically required to completely combust all of the fuel being gasified. Equivalence ratio is expressed as a percentage and is calculated using the following formula:

Equivalence ratio = (Actual air supply)/(Theoretical Air requirement)

If the equivalence ratio is less than 100%, it means that there is not enough oxygen present in the gasification process to fully combust all of the fuel. In this case, the gasification process may be incomplete, resulting in a lower gas yield and lower heating value of the product gas[24]. On the other hand, if the equivalence ratio is greater than 100%, it means that there is excess air or oxygen present in the gasification process. This excess air can lead to lower gasification efficiency and higher levels of unwanted by-products like carbon monoxide and nitrogen oxides.

Therefore, maintaining an appropriate equivalence ratio is important for optimizing gasification performance and product gas quality. The optimal equivalence ratio can vary depending on the specific gasification technology and fuel being used[25].

To calculate the stoichiometric air flow rate per unit mass, we need to determine the amount of air required to completely combust the biomass sample[26,27]. First, let's calculate the mass fraction of each element in the biomass sample using the ultimate analysis. Then, we can write the balanced chemical equation for the combustion of the biomass sample:

$$C_xH_yO_zN_aS_b + [x + (y/4) - (z/2) - (a/2) - (b/2)](O_2 + 3.76N_2) \rightarrow xCO_2 + (y/2)H_2O + (a/2)N_2 + (b/2)SO_2 + [x + (y/4) - (z/2) - (a/2) - (b/2)]3.76N_2$$

where x, y, z, a, and b are the stoichiometric coefficients for carbon, hydrogen, oxygen, nitrogen, and sulfur, respectively.

To balance the equation, we can use the mass fractions of each element in the biomass sample and the molar masses of the elements:

- Molar mass of carbon = 12 g/mol $x = 0.5/12 = 0.0417$ (for carbon)
- Molar mass of hydrogen = 1 g/mol $y = 0.06/1 = 0.06$ (for hydrogen)
- Molar mass of nitrogen = 14 g/mol $z = 0.434/16 = 0.0271$ (for oxygen)
- Molar mass of sulfur = 32 g/mol $a = 0.005/14 = 0.000357$ (for nitrogen)
- Molar mass of oxygen = 16 g/mol $b = 0.001/32 = 3.13e\text{-}5$ (for sulfur)

Plugging these values into the balanced chemical equation, we can see that 5.5 moles of O_2 and 20.7 moles of N_2 are required for every mole of biomass:

$$\begin{aligned} &C_{0.0417}H_{0.06}O_{0.0271}N_{0.000357}S_{3.13\times10^{-5}} + 5.5(O_2 + 3.76N_2) \\ &\qquad \rightarrow CO_2 + 0.5H_2O + 0.000357N_2 + 3.13 \times 10^{-5}SO_2 + 20.7N_2 \end{aligned}$$

Finally, to calculate the stoichiometric air flow rate per unit mass, we can use the mass fraction of the biomass sample's carbon content and the stoichiometric equation:

- Mass fraction of carbon = 50%
- Mass of biomass sample = 1 kg (assuming a unit mass)
- Mass of carbon in biomass sample = 0.5 kg
- Moles of biomass sample = 0.5/12 + 0.06/1 + 0.434/16 + 0.005/14 + 0.001/32 = 0.0601 mol
- Moles of air required = 5.5 × 0.0601 = 0.3305 mol
- Mass of air required = 0.3305 × 28.97 = 9.57 kg

- Stoichiometric air flow rate per unit mass = 9.57/1 = 9.57 $kg_{air}/kg_{biomass}$

Therefore, the stoichiometric air flowrate per unit mass for the biomass sample in the gasification process is 9.57 $kg_{air}/kg_{biomass}$. This means that for every kilogram of biomass sample, 9.57 kg of air are needed to completely combust it. Therefore, changing equivalence ratio can be controlled due to control the flow rate of gasification agent entered the gasifier.

3.2. Effect of equivalence ratio

In gasification propagation, the pyrolysis section takes place in the gasifier section in the absence of oxygen, and it must be between 0.30 and 0.40 for optimal yields as shown in **Figure 2**. ER is more significant in gasification since it is based on an air deficiency and represents a portion of the total amount of stoichiometric air. **Figure 2** shows the gas conformation at high ER, CO was reduced while H_2 was elevated till equal to 0.35 then declined that because of the oxidation of H_2 and CO to H_2O and CO_2; reducing the H_2 yield. The oxidation reaction uplifts CO_2 and declines CO in the syngas through the following reactions:

Oxidation reaction to produce CO: $C + 0.5O_2 = CO$
Oxidation reaction to produce CO_2: $C + O_2 = CO_2$

It's worth noting that the specific effects of equivalence ratio can vary depending on the feedstock used, gasifier design, operating conditions, and other factors. Gasification is a complex process, and finding the optimal equivalence ratio requires careful consideration of these factors to achieve the desired gasification products and process performance.

Consequently, the equivalence ratio (0.35–0.4) with moisture content (>10%), donates an enhanced yield of syngas composition with practical amounts of tar content.

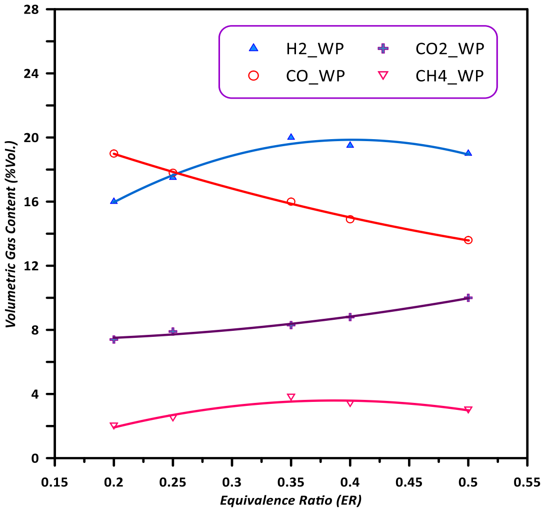


Figure 2. Volumetric gas content vs. equivalence ratio (ER).

3.3. Effect of different gasification agent

The selection of the gasification agent is a pivotal consideration influenced by various factors, such as the desired composition of the syngas, the design of the gasifier, the characteristics of the feedstock, and the intended application of the resulting syngas. Each gasification agent presents distinct advantages and considerations, underscoring the significance of making an appropriate choice to optimize the gasification process and attain the desired properties of the syngas.

The composition of the syngas is also influenced by the choice of gasification agent. In the case of exhaust gas as the gasification agent, the expected volumetric percentage of carbon monoxide (CO) in the syngas is approximately 15%–25%, while air gasification yields a slightly lower range of 10%–20%. The presence of CO in the syngas is valuable as it can be utilized as a fuel or feedstock for a variety of applications. Additionally, the expected volumetric percentage of hydrogen (H_2) in the syngas is approximately 5%–15% for exhaust gas and 5%–10% for air gasification. Hydrogen holds significance in applications such as fuel cells or as a reducing agent in industrial processes. Furthermore, methane (CH_4), a byproduct of gasification, typically constitutes around 1%–5% of the syngas when exhaust gas is used, and approximately 1%–3% when air is employed. Methane contributes to the heating value of the syngas.

Figure 3 provides a visual representation of the impact of exhaust gas or air as gasification agents on the volumetric gas content percentage at various equivalence ratios. The utilization of exhaust gas as a gasification agent offers cost and environmental benefits compared to the use of air. Biomass gasification using exhaust gas results in syngas with higher concentrations of hydrogen and carbon monoxide compared to air gasification due to the lower oxygen content in exhaust gas. Conversely, when air is used as the gasification agent, the production of carbon dioxide surpasses that of exhaust gas, which is enriched with carbon dioxide. Additionally, **Figure 3** illustrates that exhaust gas yields a substantial amount of methane gas.

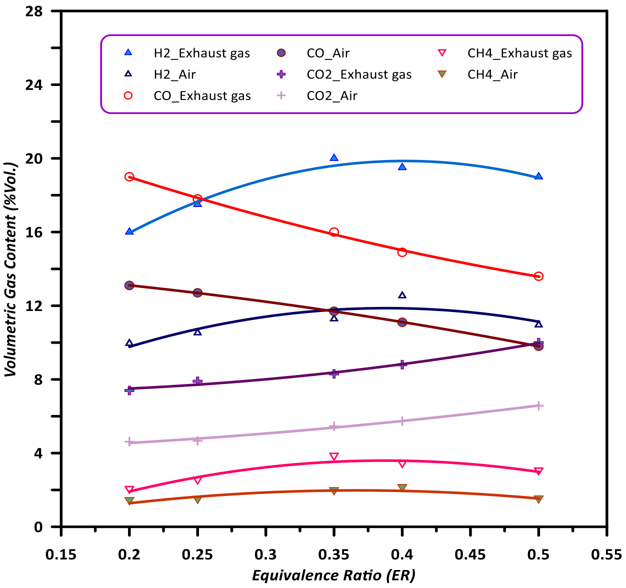
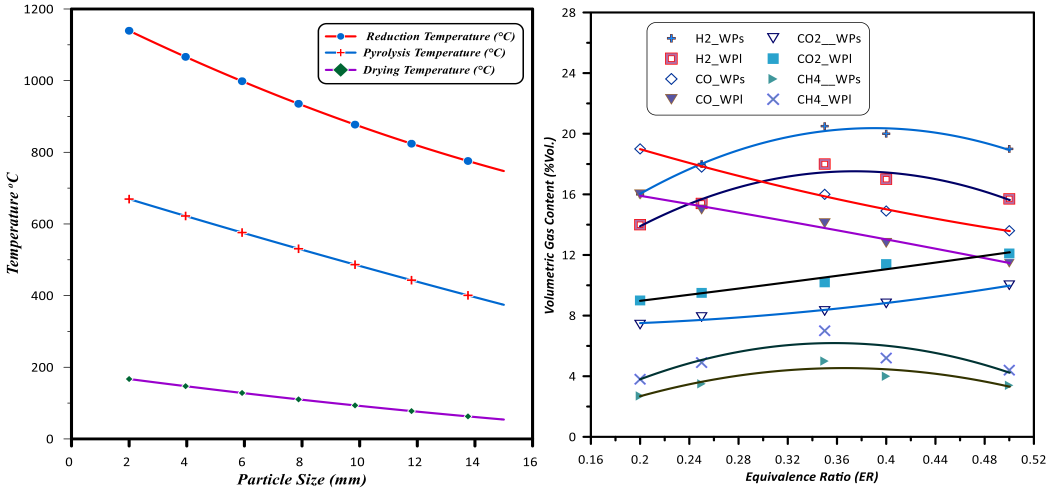


Figure 3. Various gasification agent vs. the volumetric gas content at different equivalence ratio.

3.4. Gas composition of various feedstock particle size

The particle size of the feedstock used in gasification can significantly influence the composition of the resulting syngas. Optimizing the particle size distribution of the feedstock is crucial for achieving the desired gasification performance and syngas quality. This optimization often requires striking a balance between reactivity, gasification efficiency, tar formation, and overall process economics. Experimental studies and system-specific evaluations are necessary to determine the optimal feedstock particle size for a particular gasification system.

In addition, smaller particles exhibit a larger surface-to-volume ratio but a lower total surface area, resulting in a higher density of active sites. However, when particle size is reduced from 3.14 cm^3 to 0.2 cm^3, the temperature in all stages decreases and the production of char and gas decreases as shown in **Figure 4a,b**. This reduction can be attributed to the limitations in heat transfer within larger particles, leading to higher temperature gradients inside the particles. The outer char layer can act as a barrier, hindering the release of volatiles and increasing the amount of char produced as well as the residual volatile material present in the char. Smaller particle sizes undergo cracking and develop pore structures, which leads to an increase in the concentration of carbon dioxide (CO_2). However, the reduction in particle size has a minimal impact on the H_2/CO ratio. **Figure 4b** illustrates the effect of different sizes (WP_l, WPs) of feedstocks at various equivalence ratios (ER) on syngas composition and determines the corresponding operating conditions. The presence of excess air in the combustion zone promotes oxidation reactions, facilitating tar cracking.



(a) **(b)**

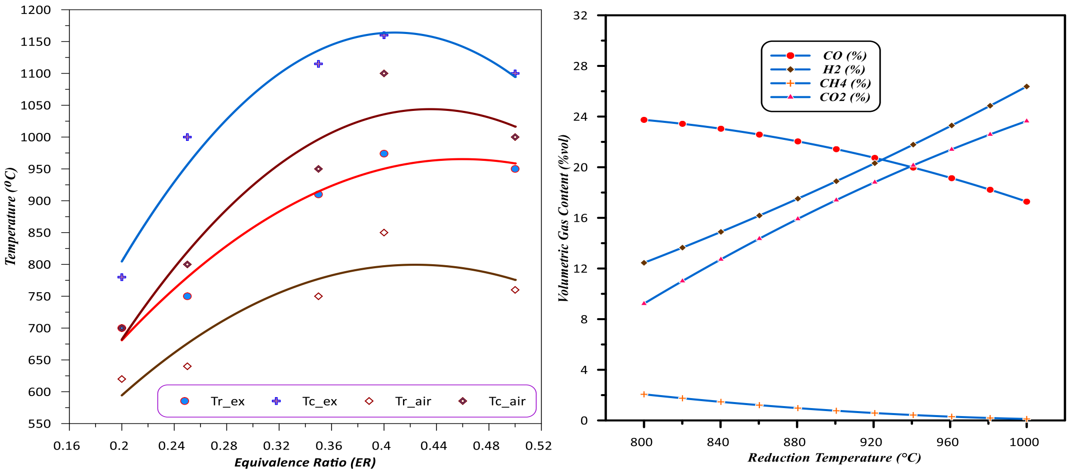
Figure 4. **(a)** gasification temperatures vs. different particle size; **(b)** volumetric gas content vs. equivalence ratio (ER) using different particle size.

The use of small particle size (WP_l) enhances the release of volatiles due to an increased heat transfer area during the pyrolysis process. Smaller woody materials, in particular, yield more syngas than larger ones do; the constructive properties of syngas are reached at feedstock sizes of 5 to 20 mm.

3.5. Effect of gasification temperature

The temperature plays a crucial role in gasification processes, and it has a significant effect on the composition of gasification products. Here are the key effects of temperature on gasification products. It's important to note that the optimal gasification temperature depends on various factors, including the type of feedstock, desired syngas composition, reactor design, and process objectives. Finding the appropriate temperature range requires careful consideration and optimization to achieve the desired gasification products and process performance.

The reduction temperature is a critical parameter that varies depending on the choice of gasification agent and the equivalence ratio as shown in **Figure 5a**.



(a) **(b)**

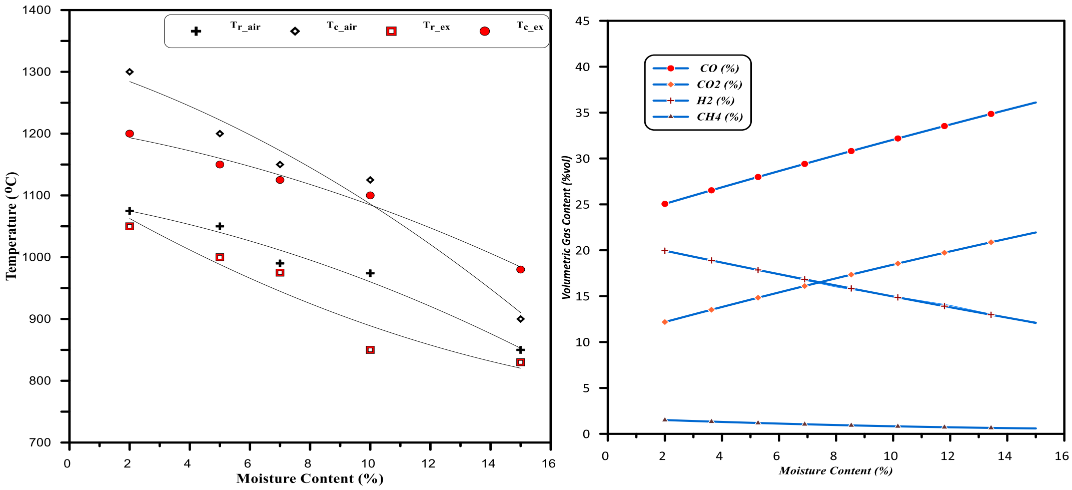
Figure 5. **(a)** gasification agent vs. the temperature distribution across the gasifier for gasification of wood pellet D = 5 mm; **(b)** gasification temperature vs volumetric gas content using exhaust gas and spherical biomass D = 5 mm.

Based on results shown in **Figure 5b**, we can observe certain trends and relationships between the gasification temperature and the percentage of syngas components. Generally, as the gasification temperature increases, the percentage of hydrogen in the syngas tends to increase. This is because higher temperatures promote the cracking and reforming reactions that result in the production of more hydrogen. So, an increase in gasification temperature typically leads to an increase in the H_2 percentage. The CO percentage in syngas tends to decrease with an increase in gasification temperature. This is because higher temperatures favor the water-gas shift reaction, which converts carbon monoxide into carbon dioxide and hydrogen. As a result, the CO content decreases as the temperature rises.

The CO_2 percentage in syngas generally shows a trend of increasing with higher gasification temperatures. This is because at elevated temperatures, the reactions involving the gasification of carbonaceous materials tend to produce more carbon dioxide. Therefore, an increase in gasification temperature often leads to a higher CO_2 content in the syngas. Methane (CH_4) percentage is relatively low and tends to decrease as the gasification temperature increases. This is because higher temperatures promote the thermal cracking of methane into simpler hydrocarbons and eventually into carbon monoxide and hydrogen. Therefore, an increase in temperature usually results in a decrease in the CH_4 content of the syngas.

3.6. Effect of biomass moisture content

The moisture content of biomass plays a crucial role in gasification processes, particularly when exhaust gas or air is used as the gasification agent. **Figure 6a** illustrates the influence of moisture content on temperature in both the reduction zone using exhaust gas or air as the gasification agent. When exhaust gas is utilized, the low oxygen concentration slows down reactions and lowers temperatures in both the combustion and reduction zones. Conversely, the use of air as the agent raises temperatures due to the higher oxygen content, which accelerates reaction rates and increases the temperature profile.



(a) **(b)**

Figure 6. (a) moisture content vs. the temperature distribution across the gasifier; **(b)** moisture content vs. volumetric gas content.

In terms of syngas composition, higher moisture content dilutes the energy content of the syngas, resulting in a lower heating value. As shown in **Figure 6b**, gasifying biomass with high moisture content can increase the concentrations of hydrogen (H_2) and carbon dioxide (CO_2) in the syngas due to steam reforming reactions. At the same time, it can decrease the concentrations of carbon monoxide (CO) and methane (CH_4) due to the water-gas shift reaction and increased steam reforming reactions. Conversely, biomass with lower moisture content generally leads to higher heating values, as the absence of excess moisture increases the energy content of the syngas. Additionally, lower moisture content promotes higher concentrations of carbon monoxide (CO) and methane (CH_4) in the syngas due to enhanced carbon conversion during gasification. It also reduces the concentrations of hydrogen (H_2) and carbon dioxide (CO_2) due to limited availability of water for steam reforming reactions.

Drying biomass to reduce its moisture content can improve gasification efficiency and syngas quality. However, it is essential to strike a balance as excessively dry biomass can lead to increased gasification temperatures and potential issues like reactor bed agglomeration. Therefore, finding the optimal moisture content for gasification requires careful consideration of various factors, including the specific biomass feedstock, gasifier design, and process objectives.

4. Limitations and recommendations

4.1. Limitations of the article

1) Short-term focus: The article primarily concentrates on the short-term operational success and experimental results of the innovative downdraft gasifier design. A more comprehensive understanding of its long-term performance, reliability, and maintenance requirements is lacking.
2) Limited feedstock Analysis: Although various biomass feedstocks are mentioned, the article does not explore the unique gasification characteristics, potential constraints, and variations associated with different feedstock types.
3) Inadequate environmental assessment: The article highlights reduced environmental impact but does not provide a comprehensive assessment, including a life cycle analysis, to holistically evaluate the system’s sustainability.
4) Limited economic insights: Although low-cost materials are mentioned, the article lacks an in-depth economic analysis or cost-effectiveness evaluation, essential for technology adoption considerations.

4.2. Recommendations

1) Long-term evaluation: Conduct comprehensive long-term performance testing and monitoring to assess the system’s real-world reliability, durability, and maintenance needs. This will provide essential insights for practical applications.
2) Diversify feedstock evaluation: Expand experimental investigations to encompass a broader range of biomass feedstocks to uncover their specific performance attributes and limitations.
3) Comprehensive environmental impact assessment: Conduct a thorough life cycle analysis to evaluate the system’s overall environmental footprint, encompassing resource use, emissions, and waste generation.
4) Economic feasibility analysis: Perform a detailed economic study to assess the cost-effectiveness of implementing the innovative downdraft gasifier design compared to existing technologies. Evaluate payback periods and potential financial incentives for adoption.

Addressing these limitations and adopting the provided recommendations will facilitate the practical implementation and broader adoption of the innovative gasification technology across diverse applications and regions.

5. Conclusion

The innovative downdraft gasifier design, which employs exhaust gas as the gasification agent, has proven its successful operation and versatility with various biomass feedstocks, notably wood pellets of different sizes (<20 mm to 20–50 mm). This system efficiently produces clean syngas suitable for both heating and electricity generation. Experimental investigations spanned a temperature range of (620 to 1250 ℃) and an equivalence ratio range of (0.2 to 0.5). The resulting syngas composition included essential components like H_2, CO, CO_2, and CH_4, aligning with traditional gasification processes.

The utilization of exhaust gas as the gasification agent represents a pioneering advancement, reducing energy input and greenhouse gas emissions, enhancing environmental sustainability. The primary gasification agent's flow rate was 440 m^3/h, and the producer gas's exit temperature ranged from 300 to 650 ℃, influenced by the moisture content of the biomass feedstock. Furthermore, the reaction zone temperature varied based on the equivalence ratio (ER) for exhaust gas (700–974 ℃) and air (620–850 ℃), with moisture content impacting the temperature as well (830–1050 ℃ for exhaust gas and (850–1050 ℃ for air).

The syngas predominantly comprised carbon monoxide (14.4%–19.2%), hydrogen (16%–20%), carbon dioxide (7.1%–11.2%), and a minor quantity of methane (2%–3%). This innovative downdraft gasifier design offers substantial promise as a renewable energy system due to its use of cost-effective materials and reduced environmental impact. These advancements open doors for the widespread adoption of downdraft gasifiers, particularly in thermal and power applications, with a particular focus on their potential in developing nations.

Author contributions

Conceptualization, SE; methodology, SE; software, BH; formal analysis, BH; investigation, SE; data curation, SF; writing—original draft preparation, SE; writing—review and editing, SF, MI and NNB; visualization, BH; supervision, NNB; project administration, NNB. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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