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Evaluation of the Impact of Biomass Moisture Content on the Performance of the Circulating Fluidized Bed Gasifier

Maharshi Thakkar [1], and Vishal Singh [2*]

[1,2*] The Charutar Vidya Mandal (CVM) University, Department of Mechanical Engineering, A. D. Patel Institute of Technology (ADIT), Vallabh Vidyanagar, Anand, Gujarat, India

maharshi.thakkar@cvmu.edu.in, vishalsingh@alumni.iitd.ac.in, vishal.singh@cvmu.edu.in

Abstract

Bioenergy's contribution to global sustainable development has increased rapidly in recent years. This study investigates the effect of biomass quality, specifically moisture content, on the performance of the Circulating Fluidized Bed Gasifier (CFBG). Sugarcane bagasse with moisture contents of 8.3 wt.%, 15.1 wt.%, and 25.6 wt.% was used for the investigation. Air is utilized as a gasification agent. The equivalence ratios (ER) used in the study were 0.2, 0.3, 0.4, and 0.5. All testing conditions used a bed material composed of 60% sand and 40% raw dolomite by mass. The system performance in terms of the effect of biomass moisture content on syngas composition, carbon conversion efficiency, syngas LHV, tar generated, cold gas efficiency, and gas yield was studied. The results showed that increasing the moisture content in biomass reduced the reactor temperature by nearly 7-10% under the same operating circumstances. As the moisture content increased from 8.3% to 25.6%, the hydrogen content in the syngas was decreased by nearly 3%, 3.5%, 2.9% and 2.6% for ER values of 0.2, 0.3, 0.4, and 0.5, respectively. The biomass with the lowest moisture content of 8.3 wt.% had the highest syngas LHV of 4.6 MJ/m3 at the ER of 0.4, while the biomass with the highest moisture content of 25.6 wt.% had the lowest syngas LHV of 3.1 MJ/m3 at the ER of 0.2. Carbon conversion efficiency, cold efficiency, and gas yields were all considerably affected by the rise in biomass moisture content. Char and tar yields climbed with increasing biomass moisture content, reaching their peak for all employed ERs for biomass with a moisture level of 25.6 wt.%.

Index-words: *Biomass Gasification, Bagasse, Equivalence Ratio, Fluidized Bed.*

I. Introduction

With rising air pollution from the open burning of waste materials worldwide, governments are seeking sustainable alternatives for biomass waste disposal. Driven by global industrialization and agricultural expansion, production of various wastes has surged, drawing significant attention to their potential conversion into biofuels [1, 2]. The conversion of biomass into syngas using gasification is a promising method for generating an alternative fuel while reducing greenhouse gas emissions [3]. Gasification technologies convert solid biomass into syngas consisting of carbon monoxide, hydrogen, methane, and nitrogen, which can then be used as fuel for a variety of applications [4, 5]. This technology could play a crucial role in the transition to a more sustainable energy future. Furthermore, the use of syngas can reduce reliance on fossil fuels and the negative impacts of waste management [6, 7]. Fluidized bed technology has gained popularity in recent years as a viable alternative for waste-to-energy conversion due to its superior fuel adaptation [8, 9] and high conversion efficiency. New design developments in fluidized bed gasification technology, such as bubbling, circulating, dual, and two-stage, have increased its large-scale use [10-13]. The physical characteristics of biomass have a substantial influence on syngas quality and fluidized bed gasifier performance [14, 15]. However, few studies have been conducted to investigate the effect of biomass moisture content on fluidized bed gasifier performance [16], as different types of raw biomass may contain greater amounts of Moisture (more than 20%), limiting the use of fluidized bed gasification technology [17]. Higher heat and mass transfers during fluidized bed gasification have been shown to increase gasification reaction rates, resulting in greater carbon conversion and gas yields. However, higher moisture content in the biomass may lower the reactor temperature by reducing heat transfer rates, affecting the performance of fluidized

* Corresponding author

bed gasifier systems and reducing their suitability for biomass with higher moisture content, such as agricultural residues and municipal solid wastes, without pretreatment [16, 18]. As a result, biomass pretreatment techniques such as torrefaction are becoming increasingly attractive for use in fluidized bed gasifiers [19].

This study examines how moisture content in biomass affects the performance of a circulating fluidized bed gasifier system. It also underlines the necessity for additional research into reducing the harmful impacts of increased Moisture on reactor performance. By optimizing biomass moisture levels, the CFBG system performance can be maximized, allowing for the utilization of biomass with higher moisture content, such as agricultural wastes and municipal solid wastes, while minimizing any drawbacks associated with excess moisture content of biomass during fluidized bed gasification.

II. Materials and Methods

A. Materials characterisation

Sugarcane bagasse was selected as a feedstock. The proximate analysis data for bagasse with varying moisture content are shown in Table 1. As a moisture concentration of up to 15 wt.% is recommended for the gasification process [18], one sample with a higher moisture content is chosen for the study to evaluate the issues associated with high moisture content during gasification. Based on the literature [20] and previous investigation [21], a bed containing sand and dolomite was chosen for the study. Dolomite was chosen as a catalyst because of its potential to reform tar in the reactor [22]. Table 1 shows the parameters of biomass and bed materials. The proximate analysis followed ASTM guidelines. The moisture content of biomass was determined by heating it in a hot air oven at 120ºC until it reached an identical weight. The syngas composition was determined using the Sigma Make gas chromatograph with a Thermal conductivity Detector and a Flame Ionization Detector. For detecting the hydrogen content in the syngas column, the temperature of the gas chromatograph was maintained at 70 70ºC, and Argon gas was used as a carrier gas at a pressure of 5 kg/cm^2.

Table 1: Proximate analysis and Ultimate analysis of Bagasse and Properties of bed materials

Proximate Analysis (wt %, dry basis)			
	Sample 1	Sample 2	Sample 3
Moisture	8.3	15.1	25.6
Volatile Matter	78.3	69.6	58.1
Ash content	3.1	2.9	2.8
Fixed Carbon	10.3	12.4	13.5
Ultimate Analysis (wt %, dry basis)			
C	47	45	42
H	6.5	7.8	8.3
O	42.5	43	44.5
N	0	0	0
Sand Particle Density: 2500 kg/m^3, Particle Size: 0.5 to 0.7 mm			
Dolomite Particle Density: 1100 kg/m^3, Particle Size: 0.3 to 0.5 mm			

B. Experimental methods

Figure 1 (a) and (b) illustrate the schematic diagram and the actual setup of the 15 kWth capacity circulating fluidized bed gasifier (CFBG) developed. Figure 1 (a) illustrates that the primary air supply was utilized to provide the air necessary for rapid fluidization within the reactor, while the secondary air supply was employed to recirculate the unburned biomass and bed material that had been carried away by the syngas. Provisions for steam supply were established to facilitate the air-steam gasification process. A comprehensive description of the setup and experimental procedure can be found in Ref. [23]. The bed, composed of 60% sand and 40% raw dolomite, was initially prepared within the reactor, and its temperature was subsequently increased using the conventional charcoal heating method. The supply of biomass with higher moisture content caused an increase in the amount of heated charcoal required to increase the temperature within the reactor. The regenerative blower was positioned at the base of the reactor to deliver air at high velocities (1.5 to 2.5 m/s) within the reactor, thereby sustaining the rapid fluidization required for the operation of the circulating fluidized bed gasifier. The equivalence ratio (ER) in the experiments was adjusted by modifying the biomass supply rate using a variable frequency drive. The air velocity

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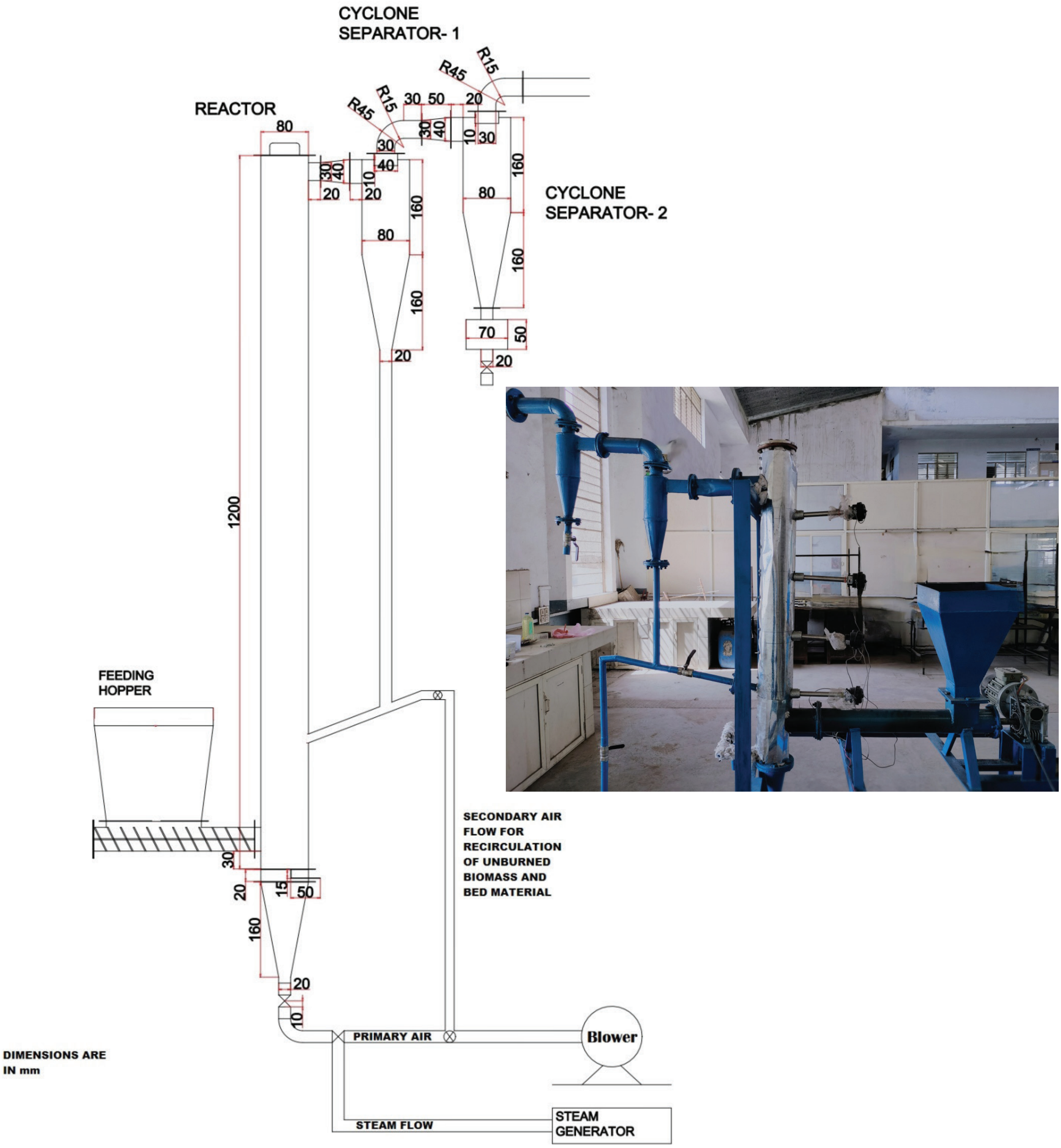
was kept constant to prevent alterations in the bed fluidization regimes and was maintained at 1.50 m/s, measured using the hot wire anemometer, having an accuracy of 0.01 m/s. The biomass supply rates ranged from 5 kg/h to 13 kg/h, depending upon the required equivalence ratio (ER). The syngas sampling was started at a particular ER condition once the steady state is reached (which normally requires 25-30 minutes after adjusting the biomass flow rate) inside the reactor in terms of the reactor temperature measured by the K-type thermocouple, as shown in Figure 1 (b), having the accuracy of ±2.5°C.



(a) (b)

Figure 1: (a) Schematic Diagram and (b) Actual Setup of the Circulating Fluidized Bed Gasifier Developed.

The detailed methodology followed for gas sampling, tar sampling, and system performance analysis is available in Ref. [23]. Each experiment was conducted at the specified equivalence ratio until the steady state condition was reached inside the reactor.

III. Results and Discussions

A. Effect of biomass moisture content on reactor temperature and Hydrogen content in the syngas

Sugarcane bagasse of different moisture content, 8.3, 15.1, and 25.6 wt.%, was used as a feedstock at the ER of 0.2, 0.3, 0.4, and 0.5. The effect of biomass moisture content on reactor temperature at different equivalence ratios is shown in Figure 2. As shown in Figure 2, with the increase in the moisture content, the reactor average temperature showed a decreasing trend with the increase in moisture content from 8.3 to 25.6 wt.% reactor temperature reduced from 685 to 632ºC, from 732 to 682ºC, 771 to 715ºC, and 802 to 721ºC for the ER of 0.2, 0.3, 0.4, and 0.5, respectively. Regarding the hydrogen content, the rise in moisture content in biomass adversely affected the H_2 content. The reduction in hydrogen content became more significant with rising moisture levels, suggesting an adverse effect on the gas composition. This underscores the significance of regulating moisture content in biomass for efficient gas generation. The lowest hydrogen content of 4.2 vol.% was reported at the ER of 0.2 for the biomass having a moisture content of 25.6 wt.%. The highest hydrogen content of 12.2 vol.% was obtained at the ER of 0.4 for the biomass having a moisture content of 8.3 wt.%. With the further increase in ER from 0.4 to 0.5, the reduction in hydrogen content was observed as an increase in ER resulted in the promotion of oxidation reactions. Similar effect of biomass moisture content on reactor temperature and variation in reactor temperature in a comparable range of 650 ºC to 750 ºC were reported by Ref. [18], and hydrogen content variation in a similar range of 10 – 12 vol.% was also reported by Ref. [1] during the air gasification in the fluidized bed.

A sensitivity analysis was performed using the three experimentally tested moisture levels (8.3, 15.1, and 25.6 wt.%). Sensitivity was calculated as: Δ(Temperature)/Δ(Moisture). Results show that reactor temperature decreases by approximately 2.9–4.7 °C per percentage point increase in Moisture, depending on ER. Detailed data regarding the reactor temperature sensitivity to the biomass moisture content is given in Table 2.

Table 2: Reactor Temperature Sensitivity to Biomass Moisture Content

ER	Δ Temperature with increase in Moisture from 8.3 to 25.6 wt.%	Temperature Sensitivity (ºC per % Moisture)
0.2	-53 ºC	3 ºC/ per moisture %
0.3	-50 ºC	2.8 ºC/ per moisture %
0.4	-56 ºC	3.2 ºC/ per moisture %
0.5	-81 ºC	4.6 ºC/ per moisture %

**Negative sign in Δ Temperature with increase in Moisture from 8.3 to 25.6 wt.% indicates the reduction in reactor temperature with the rise in biomass moisture content.*

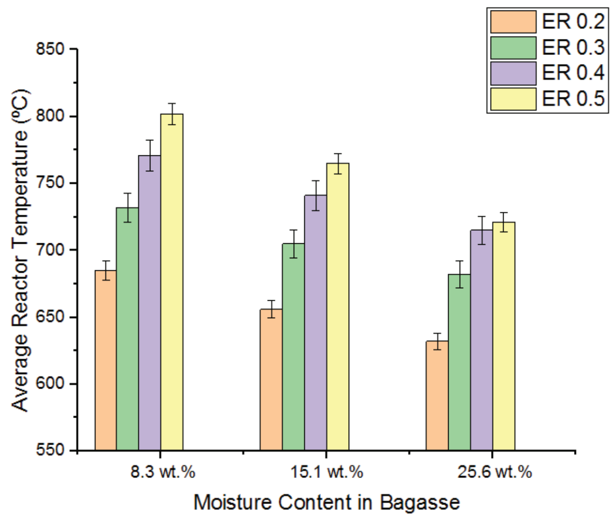


Figure 2: Effect of Biomass Moisture Content on Average Reactor Temperature at Different ERs (The error bars show the standard deviation of three similar condition tests).

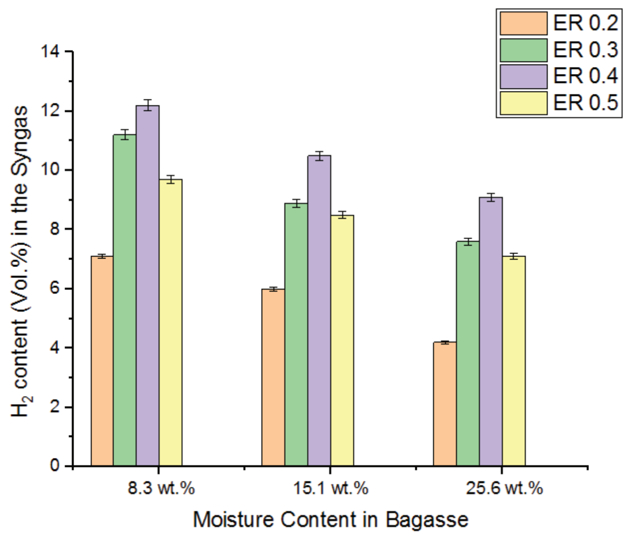


Figure 3: Effect of Biomass Moisture Content on Hydrogen Content in the Syngas (The error bars show the standard deviation of three similar condition tests).

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B. Effect of biomass moisture content on tar yield and LHV of syngas

With the increase in the moisture content from 8.3 wt.% to 25.6 wt.%, as shown in Figure 4, tar yields in the syngas were increased. These were due to the fact that the increase in the moisture content reduced the reactor temperature, which resulted in poor tar cracking. The highest tar content of 13.5 g/m^3 was observed at the ER of 0.2 and biomass having a moisture content of 25.6 wt.%. With the increase in equivalence ratios, tar content shows a decreasing trend as shown in Figure 4 as reactor temperature increases at higher ERs, which contributed towards the tar cracking. The minimum tar content obtained at the ER of 0.2, 0.3, 0.4, and 0.5 was 11.2 g/m^3, 9.9 g/m^3, 8.1 g/m^3, and 7.2 g/m^3, respectively, all at the biomass having the lowest moisture content of 8.3 wt.%. Regarding the Lower Heating Value (LHV) of the syngas as shown in Figure 5, with the increase in biomass moisture content, LHV of the syngas reduced due to a reduction in the Hydrogen content and lower formation of the gaseous products. The LHV of the syngas reduced from 3.8 to 3.1 MJ/m^3, which is by 18.5% with the rise in the moisture content from 8.3 wt.% to 25.6 wt.%. The highest LHV of 4.6 MJ/m^3 of the syngas was reported at the ER of 0.4 (due to the highest reactor temperature and higher hydrogen content in syngas) for the biomass having a moisture content of 8.3 wt.%. With the increase in ER from 0.4 to 0.5 LHV, the syngas started reducing as at higher ER oxidation reactions tend to dominate, which reduces the volatile matter in the syngas. LHV of syngas in a similar range was reported by Ref. [21] during the fluidized bed gasification of rice husk. Ref. [24] reported a similar drop in LHV of syngas with the rise in moisture content in biomass from 20% to 29%. The effect of ER on tar yield is shown in Figure 6. As shown in Figure 6, it was observed that tar content in the syngas reduced with the increase in ER due to an increase in the reactor temperature and better rates of reduction reactions. Significantly higher tar yields were observed for the lower ER 0.2 due to insufficient reactor temperature. The specific moisture content of the biomass also significantly influences gasification, with lower moisture content (e.g., 6-8 wt.%) leading to higher tar contents, while an optimal range (around 15-20 wt.%) minimizes tar formation [25].

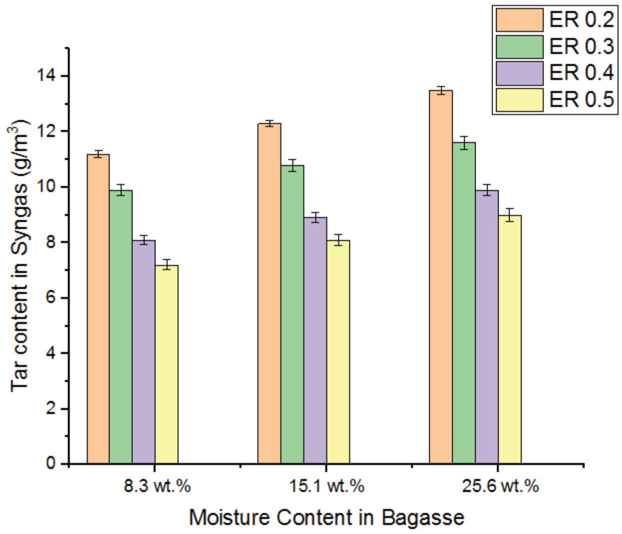

Figure 4: Effect of Biomass Moisture Content on Tar Content in the Syngas (The error bars show the standard deviation of three similar condition tests).

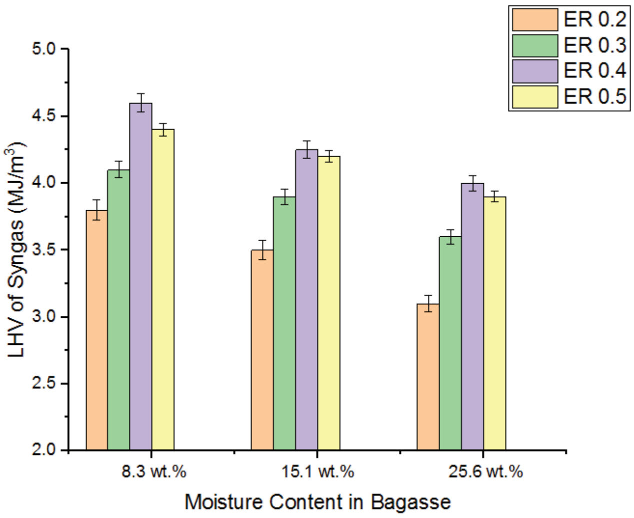

Figure 5: Effect of Biomass Moisture Content on LHV of the Syngas (The error bars show the standard deviation of three similar condition tests).

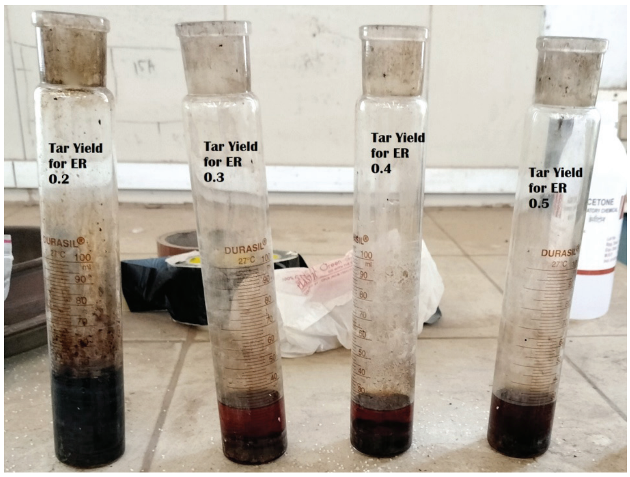

Figure 6: Effect of ER on tar yield for the bagasse having 8.3 wt.% of Moisture.

C. *Effect of biomass moisture content on cold gas efficiency and carbon conversion efficiency*

The effect of biomass moisture content on the cold gas efficiency of the CFBG system is shown in Figure 7. As shown in Figure 7, with the increase in moisture content, the cold gas efficiency of the CFBG system reduced for all the operating ERs, as higher moisture content lowered the LHV of syngas and reactor temperature. At the ER of 0.2 Comparatively, the lowest cold gas efficiency was observed at the ER of 0.2. Cold gas efficiency reduced from 43% to 36% with the increase in biomass moisture content from 8.3 wt.% to 25.6 wt.%. Similar reduction in cold gas efficiency by 6, 6.9, and 5.5% with the increase in biomass moisture content from 8.3 wt.% to 25.6 wt.% was observed for the ER of 0.3, 0.4, and 0.5, respectively. With the increase in ER above 0.4, the cold gas efficiency showed a reducing trend, as at higher ER, tar cracking reduced the hydrocarbon content in the syngas. Regarding the carbon conversion efficiency of the system, as shown in Figure 8, it was observed that with the increase in the biomass moisture content, carbon conversion efficiency showed a decreasing trend as it is a function of the reactor temperature, at the ER of 0.2 carbon conversion efficiency reduced from 58% to 48% with the rise in biomass moisture content from 8.3 wt.% to 25.6 wt.%. A similar drop in carbon conversion efficiency by 13%, 11% and 12% was observed with the rise in biomass moisture content from 8.3 wt.% to 25.6 wt.% at the ER of 0.3, 0.4, and 0.5, respectively. With the increase in ER, carbon conversion efficiency has shown continuous improvement, and it reached 78% (maximum) at the ER of 0.5 for the biomass having a minimum moisture content of 8.3 wt.%. A study conducted by Ref. [26] reported the variation in the cold gas efficiency in the range of 56 to 67% for the fluidized bed gasification of coal, which is comparable to the results obtained. While Ref. [27] reported relatively better carbon conversion efficiency around 90% due to the use of CaO catalyst as a bed material for the fluidized bed gasification of agricultural waste at similar reactor temperatures.

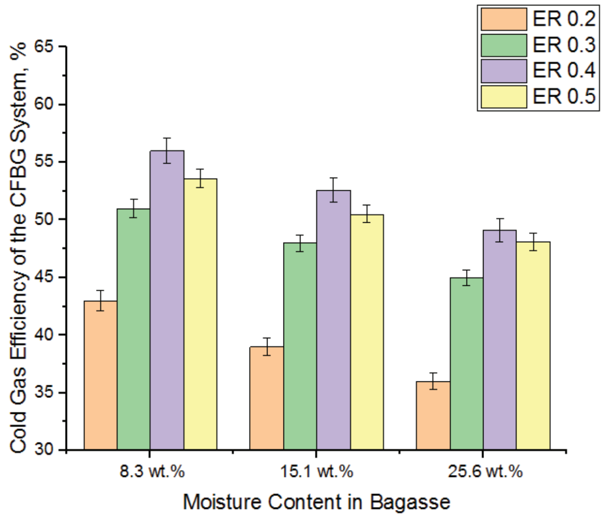

Figure 7: Effect of Biomass Moisture Content on Cold Gas Efficiency of the CFBG System (The error bars show the standard deviation of three similar condition tests).

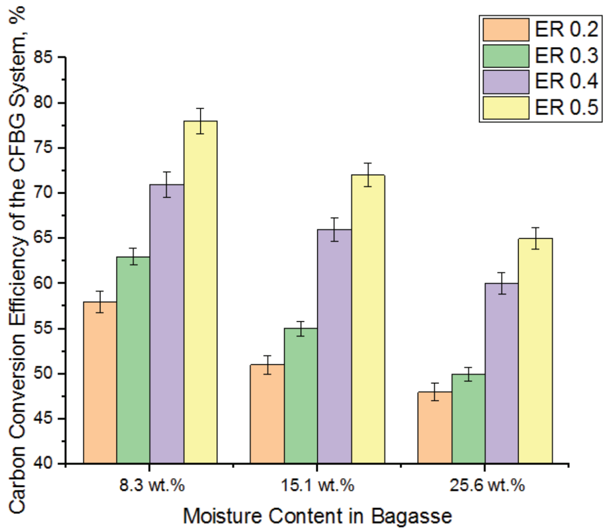

Figure 8: Effect of Biomass Moisture Content on Carbon Conversion Efficiency of the CFBG System (The error bars show the standard deviation of three similar condition tests).

D. *Effect of biomass moisture content on char yield and gas yield*

The effect of moisture content in biomass on char yield is shown in Figure 9. As shown in Figure 9, with the increase in biomass moisture content, char yield showed an increasing trend as higher Moisture lowered the carbon conversion to the gaseous products. The highest char yield of 19 % of biomass supply in kg/h was observed at the ER of 0.2 for the biomass having a moisture content of 25.6 wt.% due to the lowest operating temperature and higher moisture content in biomass. The lowest char yield of 9 % of biomass supply rate in kg/h was obtained at the ER of 0.4 for the biomass having a moisture content of 8.3 wt.%. Therefore, an ER of 0.4 is considered the condition that provides the highest solid-to-gaseous conversion rate for biomass with lower moisture content. Regarding the gas yield as shown in Figure 10, with the increase in biomass moisture content, the gas yields were reduced for all the selected ERs. The reduction in reactor temperature and the lower degradation rate of biomass having higher moisture content are the primary reasons behind the lower gas yields. At the ER of 0.2, with the rise in biomass moisture content from 8.3 wt.% to 25.6 wt.%, the reduction in gas yield by almost 27% was observed. The presence of higher Moisture lowered the heat and mass transfer reaction rates inside the reactor. Gas yield in the range of 1.2 to 2.04 m^{3}/kg of biomass was reported by Ref. [28] during the gasification of the waste polyethylene, which is comparable to the obtained range in this study, as shown in Figure 10.

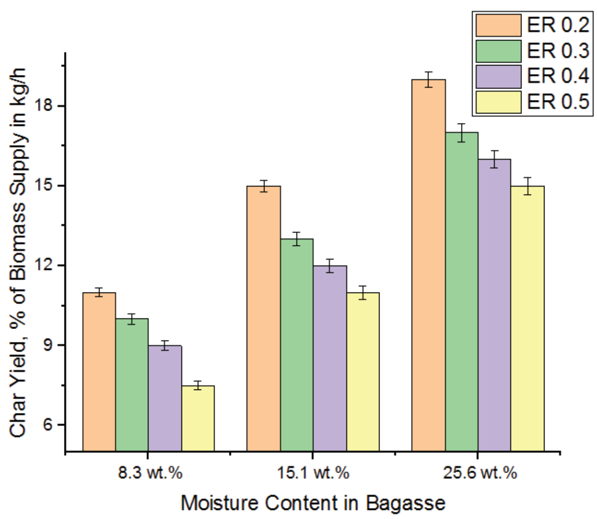

Figure 9: Effect of Biomass Moisture Content on Char Yield, % of Biomass Supply in kg/h (The error bars show the standard deviation of three similar condition tests).

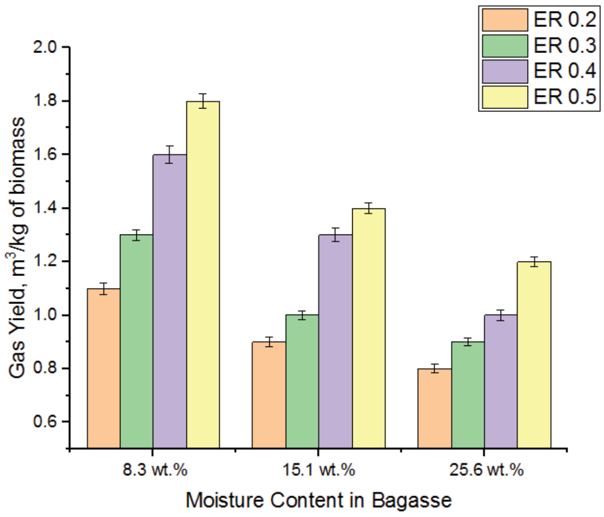

Figure 10: Effect of Biomass Moisture Content on Gas Yield, m^{3}/ kg of biomass (The error bars show the standard deviation of three similar condition tests).

E. *Effect of biomass moisture content on Energy consumption during operations*

The wood charcoals heated outside the reactor, as indicated in Figure 11, were delivered through a hopper using a Variable Frequency Drive (VFD) motor and feed screw. To increase the reactor temperature to gasification conditions, 1.2-1.5 kg of wood charcoals were heated to 500-550ºC °C (Figure 11). The charcoal heating method was adopted to quickly and cost-effectively achieve the necessary initial temperature for gasification reactions inside the CFBG reactor. Alternative reactor bed heating methods—such as electric heating, which suffers from frequent heater failures and high maintenance requirements due to elevated operating temperatures [29], and other methods that involve syngas recirculation from the gasifier outlet and burning in a gas burner provided at the reactor bottom—were avoided to minimize system complexity. During continuous operation for the biomass with 8.3 wt.% moisture content, approximately 900 grams of heated charcoals per hour were required to maintain the reactor temperature. However, when the biomass moisture content increased, so did the charcoal consumption in order to keep the CFBG system running smoothly. The charcoal consumption for biomass with 15.1 wt.% moisture content was approximately 1500 grams per hour, whereas the charcoal consumption for biomass with 25.6 wt.% was around 1900 grams per hour. As a result, as the moisture content grew from 8.3 wt.%

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to 25.6 wt.%, the biomass charcoal consumption required to maintain the ideal gasification condition inside the reactor increased by about 60%. As a result, the high moisture content in the biomass makes it difficult to use CFBG technology to convert biomass to syngas since the operating costs would rise dramatically [24].

Figure 11: Heated Wood Charcoals used for Reactor Temperature Rise.

F. *Limitations of the study and Future Scope*

- **Specific Biomass & Operating Conditions:** The study focused on sugarcane bagasse, specific equivalence ratios, and bed material composition (60% sand and 40% raw dolomite). This might limit the direct generalization of the results to other biomass types or different CFBG configurations. Further research could be conducted for other feedstocks to investigate the impact of operating variables on gasification performance to provide a more comprehensive understanding of CFBG technology's applicability across diverse feedstocks and operational parameters. The optimal moisture content for biomass gasification varies depending on the specific biomass and gasifier design, necessitating further investigation to establish universally applicable guidelines [30, 31].

- **Charcoal Heating:** The reliance on charcoal heating to initiate and maintain reactor temperature, especially its increased consumption with higher moisture content, highlights a practical limitation in terms of operational costs and sustainability. Higher moisture content in biomass also necessitates additional energy for moisture removal in biomass, which consequently reduces overall gasification efficiency [18, 32]. Further research is needed to explore integrated drying solutions that could minimize the energy penalty associated with high moisture content feedstock, potentially enhancing the economic viability of biomass gasification [18]. Further research on Agricultural waste utilization in renewable energy systems will play a pivotal role in achieving a sustainable energy ecosystem [33].

- **Optimizing Moisture Levels & Pretreatment:** By optimizing biomass moisture levels, the CFBG system performance can be maximized, allowing for the utilization of biomass with higher moisture content. This suggests future work on determining optimal moisture levels and exploring pretreatment techniques like torrefaction, which is already mentioned as an attractive option in the study conducted by different researchers [23].

IV. Conclusion

This study examined the impact of biomass moisture content on the performance of the Circulating Fluidized Bed Gasification system, focusing on reactor temperature, hydrogen yield, tar yield, lower heating value of syngas, cold gas efficiency, and carbon conversion efficiency. Bagasse samples with moisture contents of 8.3 wt.%, 15.1 wt.%, and 25.6 wt.% were selected for the study, and system performance was evaluated at ERs of 0.2, 0.3, 0.4, and 0.5. The increase in biomass moisture content from 8.3 wt.% to 25.6 wt.% resulted in a reduction of hydrogen content in the syngas by 2.6 to 3.5%, depending upon the ER. The lower heating value (LHV) of the syngas decreased from 4.6 to 4 MJ/m^3 at an ER of 0.4 as the biomass moisture content increased from 8.3 wt.% to 25.6 wt.%. The increase in moisture content from 8.3 wt.% to 25.6 wt.% in bagasse resulted in a reduction of cold gas efficiency by 5-7%, a decrease in carbon conversion efficiency by 10-13%, and a decline in gas yields by approximately 15-20%. Conversely, char yield increased by 7-8%, while tar yields rose by 1.5 to 2.3 g/m^3. The study's results indicated that moisture content in biomass significantly affects the charcoal consumption needed to maintain the desired reactor temperature profile during operations. The study indicates that reducing moisture content in biomass enhances conversion efficiency and decreases operating costs.

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