# Experimental Study of Cotton stalks Gasification in a Downdraft Reactor

# دراسة عملية لتغويز حطب القطن باستخدام مفاعل السحب لأسفل

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## الملخص

تعتبر عملية تغويز الكتلة الحيوية تقنية واعدة لتحويل المخلفات الى طاقة وللقضاء على المشاكل البيئية الضخمة المصاحبة لعملية الحرق في الحقل المفتوح. الهدف من هذه الدراسة هو دراسة عملية للأداء الديناميكى لمغوز بتصميم من نوع (إمبرت) وحجم معملى بإستخدام حطب القطن. تم استخدام الهواء كعامل تغويز وكمية الكتلة الحيوية ٤ كجم دفعة واحدة. تقييم خصائص عملية التغويز يتمثل فى تحديد القيمة الحرارية السفلى وكفاءة عملية التغويز ووقت التشغيل. غطت الدراسة معدلات سريان للهواء (٦٠-١٠٠-١٥٠-٢٠٠) لتر فى الدقيقة محققة نسبة تكافؤ تتراوح بين (٠,٣٦٢ الى ٠,٢٣٢). وقد أظهرت النتائج ان نسبة التكافؤ ٠,٣٠٤ هى الأفضل لتغويز حطب القطن حيث يعطى قيمة حرارية سفلى متوسطة للغاز الناتج تساوى ٤,٣٤ ميجا جول/م$^{٣}$ من الغاز وكفاءة تغويز ٦١,٧%.

## ABSTRACT

Biomass gasification process is considered a promising waste-to-energy conversion technique to eliminate the immense environmental issues accompanied with open field burning. The objective of this study is to experimentally study the dynamic behavior of an Imbert based design manufactured bench scale gasifier using cotton stalks as a feed stock. Air was employed as a gasifying agent with a biomass batch feed of 4 kg. The gasification process characteristics are evaluated in terms of lower heating value, gasification efficiency, and operation time. The applied air flow rates are (60, 100, 150, and 200 l/m) achieving varied equivalence ratios between 0.362 – 0.232. An optimum average lower heating value and cold gas efficiency of 4.34 MJ/m$^3$ and 61.7 % respectively are attained at equivalence ratio, ER of 0.304.

# 1. Introduction

The expanding gap between demand and consumption of energy particularly in developing countries has exacerbated the energy crisis. Furthermore, the accompanied limitations related to the fossil fuels such as the expected extinction, and pollution, force to explore alternative renewable energy sources. The alternative sources, biomass gets increasing attention, thanks to its carbon neutral feature [1]. Moreover, it is the only renewable energy source which contains carbon to be converted into convenient solid, liquid and gaseous fuels, and further into heat, electricity and transport fuels [2].

Energy from biomass can be obtained via two major routes, biochemical conversion (fermentation) and thermochemical conversion (pyrolysis, gasification, combustion) [1]. Among them, gasification is an interesting technique to convert biomass into combustible gas mixture called synthesis gas (syngas). The utilization of biomass gasification is sorely wide spreading since, it is reliable and efficient technique that can use biomass with minimum pretreatments and in the same place where it is generated. Generally, gasification involves the reaction of the solid fuel with co-reactant at temperatures range of 550-1000 °C. Co-reactants are introduced in sub-stoichiometric amounts in order to partially oxidize the fuel instead of complete oxidation to $CO_2$ and $H_2O$ [3]. The resulting gas is a mixture of carbon monoxide, hydrogen, methane, and carbon dioxide along with small amounts of light hydrocarbons. Diverse co-reactants can be used such as air., oxygen, steam, and $CO_2$ [3].

Different gasifiers are employed for this process, mainly including fixed bed, fluidized bed, and entrained flow [4]. The main difference between these reactors is distinguished by how the biomass and the oxidizer are moving inside the reactor. Compared with the fluidized bed and entrained flow gasifiers, fixed bed gasifier is more suitable for small scale applications [5]. The fixed bed includes downdraft, updraft and cross-draft gasifiers. The downdraft fixed bed gasifier has the advantage of low tar generation by cracking, as the gas passes through high temperature zone [6]. Therefore, the downdraft fixed bed gasifier is chosen in this study.

Four sub-processes, namely drying, pyrolysis, oxidation (combustion), and reduction (char gasification) overlap at a particular time along the gasifier[7].

Many researches have been conducted on downdraft gasifiers for diverse types of biomass to evaluate the gasifier performance and biomass capability of gasification. Jain [8] designed and tested an open core throat-less (stratified) gasifiers with internal diameters varying from 15.2 to 34.3 cm. The optimum values of equivalence ratio (ER), gasification efficiency, and lower heating value (LHV) were reported to be 0.40, 65%, and 4.5 MJ/m$^3$ respectively.

Guo et al. [6] used a reactor with an internal diameter of 0.42 m to gasify the corn stalk with continuous feeding option. They concluded that, the optimum equivalence ratio was 0.25-0.27 giving LHV of 5.4 MJ/m$^3$ at feeding rate of 7.5 Kg/h with gasification efficiency of 65 %.

Singh and Sekhar [9] studied experimentally and theoretically the variation in performance parameters when gasifying blends of coconut shell and rubber seed shell. The equivalence ratio range was (0.2 – 0.34) where the maximum concentration of combustible gases occurred at 0.2 and decreased at 0.3. Coconut shells conducted combustible species and conversion efficiency more than rubber seed shells.

Gai and Dong [5] studied the corn straw gasification in a stratified gasifier with two stages of air supply. The optimum ER was 0.32 giving LHV of 5.39 MJ/m$^3$. Yoon et al. [10] used a larger scale reactor to perform the gasification of rice husk and rice husk pellets and reported that, an optimum ER of 0.58 for rice husk and 0.29 for pellets with HHV of 4.5 and 5.5 MJ/m$^3$ respectively.

A co-gasification of lignite and waste wood has been investigated by Patel et al. [11] that showed a maximum LHV of 4.44 MJ/m$^3$ at 30 % wood to lignite ratio. Chen et al. [12] operated an electrically heated small gasifier at 800 °C using Biogas-derived digestate as a feed stock and obtained a LHV of 4.78 MJ/m$^3$ at ER of 0.25.

Tanczuk et al. [13] determined the influence of adding dried chicken manure to the wood pellets at constant ER of 0.21, they found that when blending wood pellets with raw chicken manure the LHV increased from 2 MJ/m$^3$ to 4 MJ/m$^3$ at 75% mixture. In order to improve the gasification process, a throat could be incorporated as referred by [14-18]

A preliminary experiment for the determination of the range of gasifying air flow rate in batch operation [16, 17] concluded that, when gasifying 9 kg and 8 kg of Oil palm fronds, the flare was observed after exceeding 200 l/m of air, then weakens after 400 l/m while the gasification time was about 34 min. Besides, preheating air upstream the gasifier enhanced the HHV from 4.66 to 5.31 MJ/m$^3$.

Galindo et al. [19] operated a stratified gasifier using Encalyptus wood with 12 kg/h as a feed stock at air flow rates of 300, 333.3 and 366.67 l/m which correspond with ER of 0.303, 0.279 and 289 respectively. They concluded a maximum LHV of 5.12 MJ/m$^3$ when operating at 0.289 equivalence ratio.

Sheth and Babu [15] studied the gasification of waste wood in batch operation of 3 kg with air flow rate varied from 30.83 to 56.67 l/m which led to 1 and 3.63 kg/h fuel consumption rate respectively, achieving ER of 0.35 and 0.179 at different moisture content.

Machin et al. [20] created a swirl flow at the combustion zone while gasifying three different types of biomass (Olive, Peach, Pine). An optimum HHV of 3.97 MJ/m$^3$ for Peach at 7.6 kg batch feed with 88.3 l/m air for 2.5 hours.

Sharma and sheth [21] studied the dynamic behavior of the gasifier using wood at air flow rate varying from 25.7 l/m to 41.13 l/m and reported that, as the air flow rate increases the biomass consumption rate linearly increase. Using air-steam gasification exhibited a calorific value of (3.64 – 4.01) MJ/m$^3$.

Nisamaneenate et al. [22] identified the optimal operating conditions for the gasification of peanut shell waste using thermal integration unit coupled to modular downdraft gasifier. The LHV was observed to increase from 3.66 to 3.79 MJ/m$^3$ and cold gas efficiency from 40.17 to 41.62 % at ER of 0.12. When operating with heat recovery at ER nearly 0.21, the carbon conversion efficiency increased by 5.75 % and a maximum LHV of 3.92 MJ/m$^3$ was obtained.

Few researchers investigated the gasification of cotton stalk, Karatas et al. [23] investigated the gasification of cotton stalk in fluidized bed reactor, they obtained a maximum LHV of 3.24 MJ/m$^3$ at ER equals 0.36. Whereas, Wang et al. [24] studied the cotton stalk pellets in a throated downdraft gasifier with separated pyrolyzer and reported a LHV of 4.22 at ER of 0.21.

Hamad et al. [25] used an electric heater to externally heat the reactor for the gasification of cotton stalks, rice straw, and corn stalks with different catalysts and concluded that, cotton stalks is more suitable for gasification process. Besides, an optimum ER of 0.25 was attained.

Most of the researches have included only steady state operation [10,13,21-25]. Limited researches have been done on the dynamic behavior of the gasification process. The aim of this work is concerned with investigating the gasification with Egyptian cotton stalk waste using throated downdraft fixed bed gasifier. Hence, the dynamic behavior of cotton stalks gasification with the influence of operating parameters; air flow rate, equivalence ratio, and gasification temperature were investigated. The study was conducted by measuring temperature profiles, producer gas composition at the transient conditions inside the gasifier. In addition, the process evaluation parameters such as, produced gas calorific value and gasification efficiency are estimated.

## 2. Experimental Setup

### 2.1 Fuel material specifications

The main source of biomass waste in Egypt is the agricultural wastes (crop residues), followed by municipal solid wastes, animal wastes, and sewage wastes [26]. Therefore, Cotton stalks as agriculture waste material is chosen for this study. The proximate and ultimate analyses of cotton stalks are presented in Table 1

Table 1: Proximate and ultimate analyses of cotton stalks [25]

<table>
<tr><th colspan="5">Proximate Analysis, Mass Fraction %</th></tr>
<tr><td colspan="2">VM</td><td>FC</td><td colspan="2">Ash</td></tr>
<tr><td colspan="2">81.24</td><td>14.48</td><td colspan="2">4.28</td></tr>
<tr><td colspan="5">Ultimate Analysis, Mass Fraction %</td></tr>
<tr><td>C</td><td>H</td><td>N</td><td>S</td><td>O</td></tr>
<tr><td>44.8</td><td>5.8</td><td>1.09</td><td>0.57</td><td>43.8</td></tr>
<tr><td colspan="5">Higher Heating Value (MJ/kg)</td></tr>
<tr><td colspan="5">15.5</td></tr>
</table>

The feed stock is shredded after open field drying to a particle size (as length) ranged from 1 to 4 cm and from 2 to 5 mm (as diameter) as shown in Fig. 1

Fig. 1: Size and shape of cotton stalks

Due to the importance of moisture content in the gasification process, it was determined based on wet basis by the oven drying method (ASTM D4442-07) [27]. The biomass is heated at 105 °C for 24 hours in a vented forced convection oven (Binder FD 23) and then weighed. The moisture content (MC) expressed in percentage was calculated according to equation (1) [27].

$$\mathrm{MC\%} = \frac{\mathrm{m_{wet}} - \mathrm{m_{dry}}}{\mathrm{m_{wet}}} \times 100 \qquad (1)$$

Where $m_{\mathrm{dry}}$ represents the mass of the fuel after heating and $m_{\mathrm{wet}}$ is the mass of fuel prior heating. The determined moisture content of cotton stalks was about 14 %. The feed stock was then provided to the gasification system.

Lower heating values (LHV) for biomass was calculated using the empirical formula that reported by Sarkar [28].

$$LHV = HHV - 2.44 \times (9H) \qquad (2)$$

Where H is the hydrogen content of biomass determined through the ultimate analysis.

## 2.2 The gasifier unit

The experimental tests are performed on a self-made downdraft gasifier. The gasification unit comprises four main parts: the reactor, the gasifier casing, the ash disposal system, and the air supply setup. A throat-type is used as the core of the gasifier reactor with the configuration and dimensions shown in Fig. 2. The core is made of a 3-mm thick steel sheet with an overall height of 0.67 m. The upper diameter of 0.32 m is tapered to 0.22 m diameter at depth of 0.46 m from the top.

This tapered section is followed by a constant diameter section of 0.22 m in diameter and 0.08 m in height. Near its lower end, five air nozzles are regularly distributed and mounted around the same circumferential level. The reactor core is ending by a convergent-divergent section with a throat of 0.13 m where both the combustion and reduction gasification zones are situated. This constricted area provides a uniform combustion across the whole area and to force all of the pyrolysis gases to pass through this narrow passage [20].

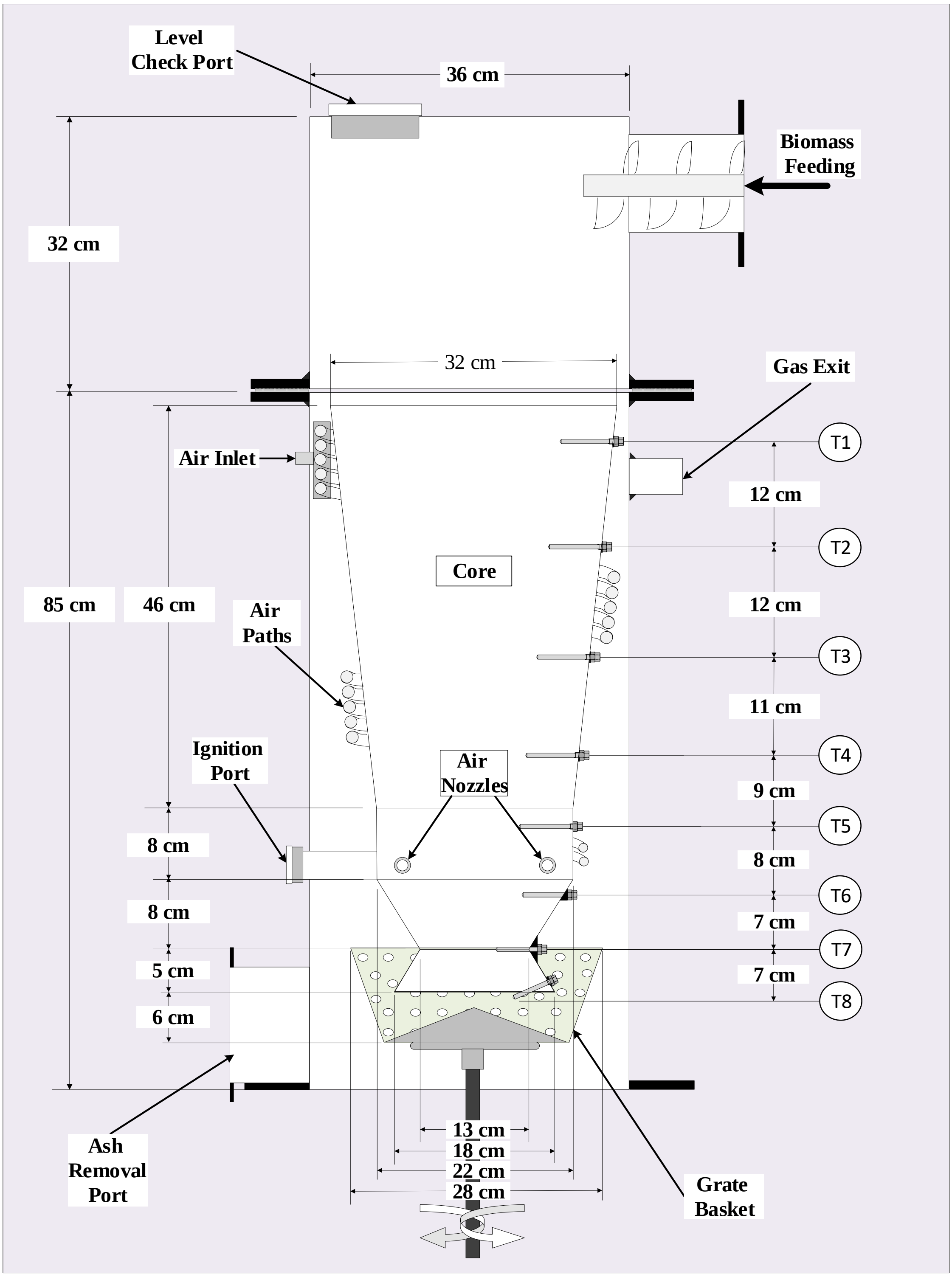

Fig. 2. The downdraft gasifier reactor

The throat is followed by the divergent part where the reduction process is commenced. The divergent part is important to lessen the gas flow velocity in order to enhance the rate of boudouard reaction and water-gas shift reaction, in order to increase the concentration of CO and $H_2$ in the producer gas and also decrease the gas temperature [20]. Under the divergent part, the ash grate is directly positioned to hold the hot charcoal for reduction reactions

The ash grate is made of perforated steel sheet with openings of 5 mm in diameter. The grate is formed on the shape of trapezoidal basket with upper and bottom diameters of 0.28 m and 0.20 m respectively, and a height of 0.11 m. Also, a small cone of 0.04 m in height is fixed on the floor of the basket. This small cone is used to enhance the conversion reduction reactions by keeping a thin layer of the hot charcoal in the path of the reactant gases stream. Besides, the cone is helpful in expelling the ashes out of the basket when the grate shaker system is working.

The core of the gasifier reactor is placed in a coaxial steel cylinder of 4 mm thickness with a height of 1.17 m and diameter of 0.36 m**.** the reactor cylinder is divided into two parts assembled together in the purpose of maintenance and connecting the biomass feeding system to the upper part. The lower part of the cylinder works as a shield around the reactor core. The air supply connection, the ignition port, the produced gas outlet port, and the ash removal port are installed at the cylinder side wall. The hot produced gas from the reactor is passing through the annular passage between the cylinder and the reactor core. The flowing hot produced gas is beneficial for the drying and pyrolysis zones moreover, to preheat the gasifying agent air.

The Feedstock is fed to the gasifier reactor by 4 kg batch through a controlled screw conveyor. The gasifying agent, (air) was circulated through a copper coil in five separate paths that are firmly wounded around the outer wall of the reactor core as shown in Fig. 2. These paths are ending with five nozzles of 5 mm exit diameter.

## 2.3 Cleaning devices

Cleaning the produced gas is often essential for downstream end-use applications. Different clean-up methodologies such as cyclone, and charcoal filter are comprised. Cyclone is connected directly to the reactor gas exit. The solid particles and some ashes are separated and collected in a collector at the lower end of the cyclone. Design and dimensions of the cyclone are based on Stairmand design [29] with main diameter (D) of 10 cm.

For further purification of the produced gas, a charcoal filter mixed with silica gel in between as a desiccator is added downstream the cyclone. The tar flowing out with the produced gas stick at the outer surface of the char blocks.

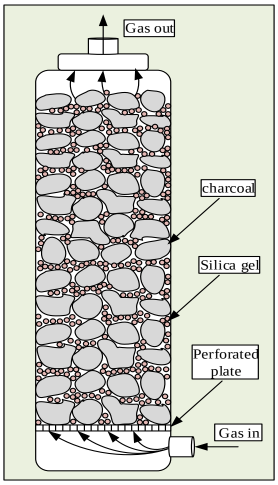

Fig. 3. Charcoal filter with silica gel

## 2.4 Instruments and measuring techniques

The temperatures are measured using eight K-type thermocouples positioned on the core wall with distances as illustrated in Fig. 2. Also, at the gas exit port an additional thermocouple is mounted to indicate the gas exit temperature. The thermocouples data are acquired using a multichannel multiplexer (KTA-295K) controlled by an Arduino board**.**

The air flow rate is monitored by two different flow meters connected in parallel, (Omega, FMA-A2323) is the primary flow meter providing a reading range of 0-100 SL/M and an accuracy of ±1%, besides (SMC brand, model:PFA511-F03N-Q) with the same range of flow and accuracy.

In order to characterize the produced gas, measurements of the gas compositions are carried out using gas chromatography (GC) of Perkin-Elmer, model (Clarus 580) with TCD detector. This GC is capable of detecting CO, $CO_2$, $CH_4$, $H_2$, $N_2$, $O_2$, $C_2H_4$, and $C_2H_6$ molecules with an accuracy of 0.01%.

A slipstream of product gas is pulled by 60 ml syringes from the bulk gas stream coming out of the charcoal filter after further sample purification by cotton.

## 3. Test calculations

Equivalence ratio, ER, is considered a key parameter that affects the gasification process. It relates the mass flow rate of both reactant materials including air and biomass fuel, in actual and stoichiometric conditions.

$$ER = \frac{\left[\frac{air\ flow\ rate}{biomass\ consumption\ rate}\right]_{actual}}{\left[\frac{air\ flow\ rate}{biomass\ consumption\ rate}\right]_{stoichiometric}}$$

where, the stoichiometric air to fuel ratio can be calculated as reported in [6] by Guo et al.

$$\left[\frac{\text{air flow rate}\left(\text{Kg}/_{\text{h}}\right)}{\text{biomass consumption rate}\left(\text{Kg}/_{\text{h}}\right)}\right]_{\text{stoichiometric}} = \frac{1.293}{0.21}\left(1.866\frac{\text{C}_{\text{daf}}}{100} + 5.55\frac{\text{H}_{\text{daf}}}{100} + 0.7\frac{\text{S}_{\text{daf}}}{100} - 0.7\frac{\text{O}_{\text{daf}}}{100}\right) \quad (3)$$

The lower heating value (LHV) of produced gas in $MJ/m^3$ can be estimated from the gas composition using the following empirical formula (4) [30] as follows.

$$LHV = [(10.79 \times H_2) + (12.636 \times CO) + (35.82 \times CH_4)] \quad (4)$$

Where $H_2$, CO, and $CH_4$ are the gases concentrations (% V/V), in the syngas.

Cold gas efficiency (CGE) of the gasification process is defined as the ratio of the energy in the product gas to the energy of biomass input (biomass energy). The CGE% applied in this work is based on the lower heating value (LHV) of both the product gas and biomass. Then it can be calculated as in [31].

$$CGE\ \% = \frac{[LHV]_{gas} \times V_g}{[LHV]_{biomass}} \times 100\% \quad (4)$$

Where $[LHV]_{biomass}$ is the lower heating value of biomass, MJ/kg and $V_g$ is the volume of produced gas per unit weight of biomass ($m^3$/kg). It can be calculated from the concentration of nitrogen in the product gas and the total amount of nitrogen entering the reactor along with air in the gasification process as in [32] by,

$$V_g = \frac{(Q_{air} \times 79)}{(N_2 \times m_b)} \quad (5)$$

Where $Q_{air}$ is the flow rate of air ($m^3$/h), $N_2$ is the concentration of nitrogen in the syngas (% V/V), and $m_b$ is biomass flowrate (kg/h).

## 4. Test procedure

Prior each experiment, 4 kg of cotton stalk (for a specified particle size range and moisture content) is poured inside the feeding hopper and fed by the screw feeder. Now, a vacuum pump is used for the startup ignition with the aid of a fire torch. Once, some feed material became red hot, the ignition port is sealed and the adjusted air flow rate for the case study is supplied. The gas sampling starts when the flare starts and repeated randomly during the experiment until the flare disappear.

## 5. Results and discussion

### 5.1 Variation of temperature and gas composition with time.

The temperatures distribution inside the gasifier, the produced gas composition and its corresponding heating value are observed to vary with time. This variation is investigated for experimental runs at different air flow rates (60, 100, 150, and 200 l/m) that reported in Figs. 4–7 respectively. As temperatures and gas composition of produced gas are varying continuously. The dynamic behavior of temperatures and produced gas composition may provide real time interpretation of the results and hence the variation of temperatures and gas composition are presented in this study. Figures. 4–7 (a) describe the temperatures distribution while, Figs. 4–7 (b) show the gas composition with time.

### 5.1.1 Temperature distribution

Temperature in the gasifier increases along the length from T1 to T6 establishing zones of drying, pyrolysis, and combustion respectively then decreases at T7 and T8 representing the reduction zone. Generally, the drying zone temperature (T1, T2) is found to be in the range of 110 °C and around 400 °C is observed for the pyrolysis zone (T3, T4). In case of batch operation, the biomass flow downward by gravity inside the reactor so, by end of the run T1-T4 increase due to biomass diminishing. Due to the bridging problem as reported by [33], an increase in T3 and T4 then decrease due to biomass collapse after bridging is noticed at some time during operation. Besides, combustion temperatures (T5 and T6) are also affected by bridging in form of T5 increase as presented in figs. 4-7 (a). While, the reduction zone temperatures (T7 and T8) showed more stability during operation with time.

Figs 4-7 (a) show that T6 represent the maximum temperature in the reactor and its maximum value is attained at 100 l/m air flow rate. When operating the gasifier at high air flow rate of 200 l/m, it is noticed that T4 and T5 jump over and exceed T6 representing expanded combustion zone up.

Meanwhile, the reduction zone temperatures (T7 and T8) are observed in relatively low range in the case of air flow rate of 60 l/m and 200 l/m than that obtained at 100 and 150 l/m as shown in figs. 4-7 (a). The average reduction zone temperatures (T7 and T8) are in the range of (635 – 455°C and 650 - 560 °C) at the air flow rates of 60 l/m and 200 l/m respectively, while, they were in the range of (710 – 590 °C and 720 - 570 °C) at air flow rates of 100 and 150 l/m respectively.

The temperatures fluctuation are observed and those may be attributed to number of reasons. One of the prominent reasons is due to the local variation of thermocouple contact with solid or gas at a particular position [21].

As, the air flow rate increases, the biomass consumption rate increases thus, the operation time of the gasification process is lessened. It was about 105 minutes at air flow rate of 60 l/m then reduced to about 20 min at 200 l/m air flow rate.

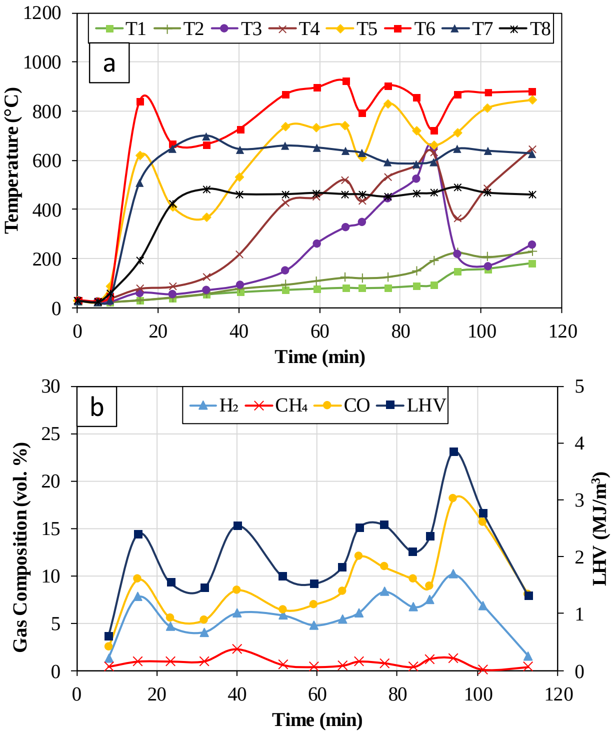

Fig. 4. Variation of temperature, gas composition and LHV over time at air flow rate of 60 l/m (ER=0.362)

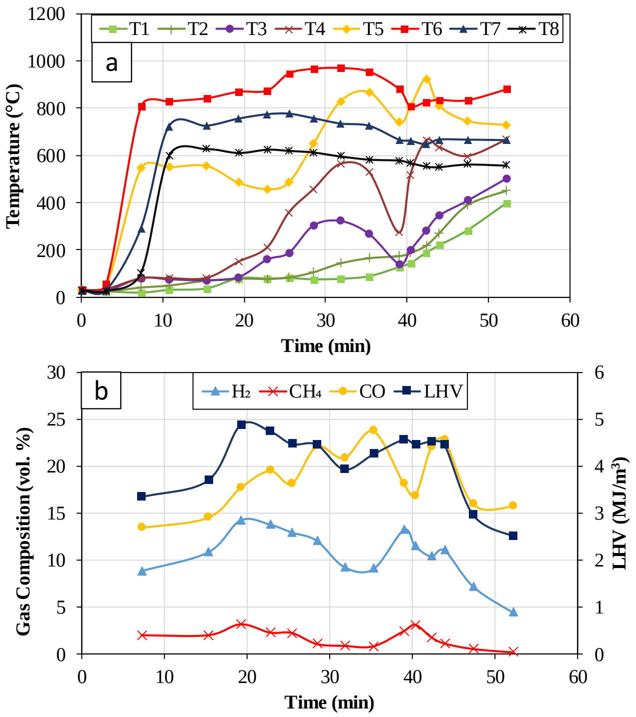

Fig. 5. Variation of temperature, gas composition and LHV over time at air flow rate of 100 l/m (ER=0.302)

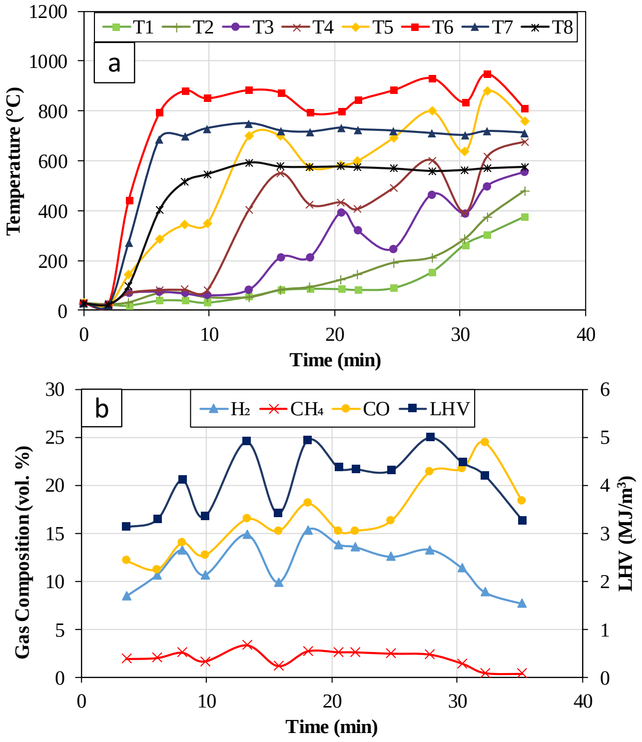

Fig. 6. Variation of temperature, gas composition and LHV over time at air flow rate of 150 l/m (ER=0.304)

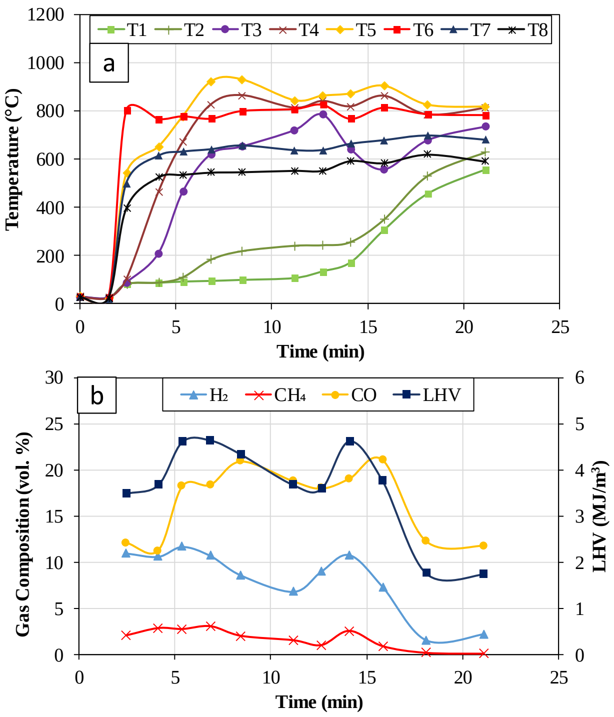

Fig. 7. Variation of temperature, gas composition and LHV over time at air flow rate of 200 l/m (ER=0.232)

### 5.1.2 Composition of produced gas

The produced gas composition varies with time depending on the instantaneous operating condition inside the reactor. Gas samples are taken randomly during operation with 60 ml syringes. The first sample of gas is taken with the preliminary appearance of flare. Figs 4-7 (b) show the dynamic variation of the combustible gas components including $H_2$, $CH_4$ and CO and the corresponding LHV with time. It is obvious that in batch operation, the gas components concentrations are highly affected by the temperature and the bridging problem inside the reactor. Particularly in small scale gasifiers, the moisture content, amount of biomass, and volatile matter in feed stock are diminishing with time. Thus, The CO concentration is noticed to increase and $H_2$ decrease in the last period of operation time. $H_2$ concentration showed a relatively lower values at air flow rates of 60 and 200 l/m compared to its values at air flow rates of 100 and 150 l/m. Moreover, at 150 l/m air flow rate, CH4 indicated a considerable stable higher volumes along the run than that obtained at 60, 100 and 200 l/m.

### 5.1.3 Produced gas heating value

The LHV of the produced gas obtained at the different studied air flow rates exhibited fairly fluctuated values at the steady operation time as presented in figs 4-7 (b). A maximum lower heating value of 5 MJ/m$^3$ is attained once at 100 l/m air flow rate, while it was achieved three times at the air flow rate of 150 l/m as illustrated in fig 5 and fig 6 respectively.

## 5.2 Effect of air flow rate.

The effect of air flow rate on biomass consumption rate is shown in Figs. 4-7. It is found that with the increase of air flow rate, biomass consumption rate increases. The increase in the air flow rate provides more oxygen to oxidize and higher amount of biomass would get combusted. The energy released will increase the rate of drying and pyrolysis. Biomass consumption rate increases not only due to a higher combustion rate, but also due to the enhanced pyrolysis and drying rate.

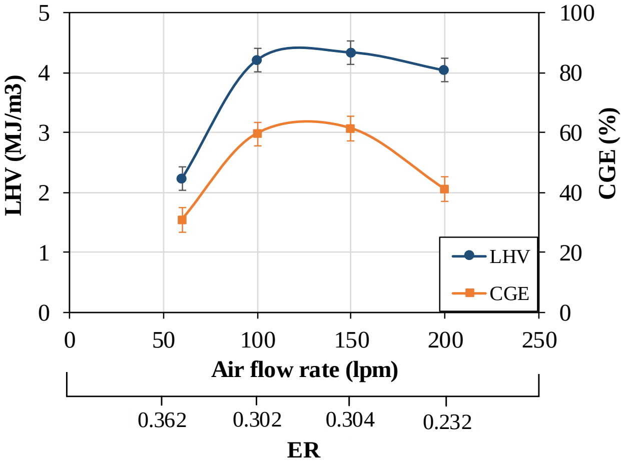

Fig. 8. Effect of ER on LHV and CGE

The average obtained values of LHV as well as the cold gas efficiency are demonstrated in Fig. 8 at different air flow rates and their corresponding ERs. LHV and CGE of the gasification process showed a significant increasing trend when the air flow rate changed from 60 l/m to 100 l/m. Almost constant values of LHV and CGE are attained till 150 l/m followed by slight decrease upon reaching 200 l/m of air flow rate. When the air flow rate is 60 l/m the combustion heat is inadequate for reduction reactions, whereas, increasing the supplied air flow rate enlarges the combustion heat to be adequate for reduction zone reactions in addition to pyrolysis and drying zones enhancement. As the air flow rate excessively increase to 200 l/m, the combustion heat being greatly enlarged compared to reduction zone requirements. Average LHVs of 2.23, 4.21, 4.34, and 4.04 MJ/m$_3$ are attained at the air flow rates of 60, 100, 150, and 200 l/m which corresponds to a calculated ER of 0.362, 0.302, 0.304, and 0.232 respectively. While the attained average CGE values are 30.77, 59.55, 61.69, and 41.07 % at ERs of 0.362, 0.302, 0.304, and 0.232 respectively.

## 6. Conclusion

The experimental investigation of the dynamic behavior of cotton stalk batch gasification in an Imbert design gasifier using air as a gasifying agent was demonstrated. From the experimental results; the following conclusions are drown, In batch operation, the biomass consumption rate is proportional to the applied air flow rate as the time of operation decreases. As the pyrolysis effect decreases with time, the volume concentration of $H_2$ in the syngas showed a reduced values whereas the CO concentration increases due to the accumulation of char in the reduction zone. The optimum operating ER for cotton stalk gasification is (0.302-0.304) which produces a considerable high lower calorific value of (4.21-4.34) and cold gas efficiency of (59.55-61.69 %).

### Nomenclature

| | |
|---|---|
| $m_{dry}$ | mass of fuel after heating, |
| $m_{wet}$ | mass of fuel prior heating, |
| $V_g$ | Produced gas yield ($m^3$/kg) |
| $Q_{air}$ | Air flow rate ($m^3$/h) |
| $m_b$ | Biomass feeding rate (Kg/h) |

### Abbreviations

| | |
|---|---|
| ER | Equivalence Ratio |
| LHV | Lower Heating Value |
| HHV | Higher Heating Value |
| VM | Volatile Matter |
| FC | Fixed Carbon |
| MC | Moisture Content in feedstock |
| GC | Gas Chromatography |
| TCD | Thermal Conductivity Detector |
| SL/M | Standard Liter Per Minute |
| daf | Dry ash free |

## References

1. Basu, P., *Biomass gasification, pyrolysis and torrefaction: practical design and theory*. 2013: Academic press.
2. Kang, Q., et al., *Bioethanol from lignocellulosic biomass: current findings determine research priorities.* The Scientific World Journal, 2014. **2014**.
3. Rada, E.C., *Thermochemical Waste Treatment: Combustion, Gasification, and Other Methodologies*. 2017: CRC Press.
4. Raman, P. and N. Ram, *Design improvements and performance testing of a biomass gasifier based electric power generation system.* Biomass and bioenergy, 2013. **56**: p. 555-571.
5. Gai, C. and Y. Dong, *Experimental study on non-woody biomass gasification in a downdraft gasifier.* International Journal of hydrogen energy, 2012. **37**(6): p. 4935-4944.
6. Guo, F., et al., *Effect of design and operating parameters on the gasification process of biomass in a downdraft fixed bed: An experimental study.* International Journal of Hydrogen Energy, 2014. **39**(11): p. 5625-5633.
7. Ismail, T.M. and M.A. El-Salam, *Parametric studies on biomass gasification process on updraft gasifier high temperature air gasification.* Applied Thermal Engineering, 2017. **112**: p. 1460-1473.
8. Jain, A.K., *Design parameters for a rice husk throatless gasifier reactor.* Agricultural Engineering International: CIGR Journal, 2006.

9. Singh, V.C.J. and S.J. Sekhar, *Performance studies on a downdraft biomass gasifier with blends of coconut shell and rubber seed shell as feedstock.* Applied Thermal Engineering, 2016. **97**: p. 22-27.

10. Yoon, S.J., et al., *Gasification and power generation characteristics of rice husk and rice husk pellet using a downdraft fixed-bed gasifier.* Renewable Energy, 2012. **42**: p. 163-167.

11. Patel, V.R., et al., *Co-gasification of lignite and waste wood in a pilot-scale (10 kWe) downdraft gasifier.* Energy, 2017. **119**: p. 834-844.

12. Chen, G., et al., *Air gasification of biogas-derived digestate in a downdraft fixed bed gasifier.* Waste Management, 2017. **69**: p. 162-169.

13. Tańczuk, M., et al., *Experimental analysis of the fixed bed gasification process of the mixtures of the chicken manure with biomass.* Renewable Energy, 2017.

14. Olgun, H., S. Ozdogan, and G. Yinesor, *Results with a bench scale downdraft biomass gasifier for agricultural and forestry residues.* biomass and bioenergy, 2011. **35**(1): p. 572-580.

15. Sheth, P.N. and B. Babu, *Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier.* Bioresource technology, 2009. **100**(12): p. 3127-3133.

16. Guangul, F.M., S.A. Sulaiman, and A. Ramli, *Gasifier selection, design and gasification of oil palm fronds with preheated and unheated gasifying air.* Bioresource technology, 2012. **126**: p. 224-232.

17. Guangul, F.M., S.A. Sulaiman, and A. Ramli, *Study of the effects of operating factors on the resulting producer gas of oil palm fronds gasification with a single throat downdraft gasifier.* Renewable Energy, 2014. **72**: p. 271-283.

18. Omar, M.M., et al., *Downdraft gasifier structure and process improvement for high quality and quantity producer gas production.* Journal of the Energy Institute, 2017.

19. Galindo, A.L., et al., *Biomass gasification in a downdraft gasifier with a two-stage air supply: Effect of operating conditions on gas quality.* biomass and bioenergy, 2014. **61**: p. 236-244.

20. Machin, E.B., et al., *Tar reduction in downdraft biomass gasifier using a primary method.* Renewable Energy, 2015. **78**: p. 478-483.

21. Sharma, S. and P.N. Sheth, *Air–steam biomass gasification: experiments, modeling and simulation.* Energy conversion and management, 2016. **110**: p. 307-318.

22. Nisamaneenate, J., et al., *Fuel gas production from peanut shell waste using a modular downdraft gasifier with the thermal integrated unit.* Renewable Energy, 2015. **79**: p. 45-50.

23. Karatas, H., H. Olgun, and F. Akgun, *Experimental results of gasification of cotton stalk and hazelnut shell in a bubbling fluidized bed gasifier under air and steam atmospheres.* Fuel, 2013. **112**: p. 494-501.

24. Wang, Z., et al., *Gasification of biomass with oxygen-enriched air in a pilot scale two-stage gasifier.* Fuel, 2015. **150**: p. 386-393.

25. Hamad, M.A., et al., *Hydrogen rich gas production from catalytic gasification of biomass.* Renewable Energy, 2016. **85**: p. 1290-1300.

26. Abdelhady, S., et al., *Viability study of biomass power plant fired with rice straw in Egypt.* Energy procedia, 2014. **61**: p. 211-215.

27. Govett, R., T. Mace, and S. Bowe, *A practical guide for the determination of moisture content of woody biomass.* University of Wisconsin, 2010.

28. Sarkar, M., et al., *Gasification performance of switchgrass pretreated with torrefaction and densification.* Applied Energy, 2014. **127**: p. 194-201.

29. Stairmand, C.J., *The design and performance of cyclone separators.* Trans. Inst. Chem. Engrs., 1951. **29**: p. 356-362.

30. Striūgas, N., et al., *An evaluation of performance of automatically operated multi-fuel downdraft gasifier for energy production.* Applied thermal engineering, 2014. **73**(1): p. 1151-1159.

31. Basu, P., *Combustion and gasification in fluidized beds*. 2006: CRC press.

32. Sharma, A., et al., *Performance evaluation of a lab-scale fluidized bed gasifier using switchgrass as feedstock.* Transactions of the ASABE, 2011. **54**(6): p. 2259-2266.

33. Inayat, M., et al., *The study of temperature profile and syngas flare in co-gasification of biomass feedstock in throated downdraft gasifier*, in *ICGSCE 2014*. 2015, Springer. p. 203-210.