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# Assessment of the Influence of Torrefied Biomass Physical Characteristics, Design and Operating Variables on Gasification Efficiency

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**Abstract:** Gasification efficiency is an important factor that determines the actual technical operation as well as the economic viability of using a gasifier system for energy production. In this study, the impact of the physical properties of torrefied bagasse and the influence of gasifier design and operating variables were investigated in a computer simulated downdraft gasification system. Results obtained from the study indicated an interrelationship between feedstock characteristics, especially with regard to feed size, design variables such as throat angle and throat diameter as well as gasifier operating conditions such as temperature of input air and feed input. These variables influenced the efficiency of the gasification process of sugarcane bagasse because of increased enhancement of combustion zone reactions, which liberated huge amount of heat that led to a rise in the temperature of the gasification process. This condition also created increased tar cracking within the gasification system, contributing to reduction in the overall yield of tar.

**Key words:** Torrefied bagasse, gasification efficiency, torrefaction, computer simulation, operating variables.

## 1. Introduction

In the wake of rising demand for renewable energy use the utilization of biomass either as a precursor for the production of biofuel or as a precursor for electricity generation has received much attention in the last decade. Biomass generation for the purpose of energy production is of increased interest as it circumvents competition involving food crops and energy, which may aid the world's food security [1]. The sugar industry in South Africa is among the largest producers of huge amounts of by-products in form of sugarcane bagasse, with increased lignocellulosic content that offers potential in thermochemical applications [2]. Pre-treatment methods such as torrefaction are often used to add value to biomass in order to ensure increased energy density, a reduction in oxygen, moisture and the propensity of smoking of the fuel generated [3]. Quite a number of pre-treatment methods have been studied and the specific application of the biomass determines the pre-treatment method to be employed [4].

Torrefaction is often referred to as mild pyrolysis because it involves heating a material between 200 and 300 °C in a chemically inactive environment. It is a pre-treatment method used to improve biomass quality for the purpose of thermochemical conversion since the process incorporates the production of a more hydrophobic biomass with increased fixed carbon content [3-5]. Torrefaction does not only involve reduction and expulsion of bulk and oxygenated compounds but also leads to a higher mass and energy yields of the torrefied biomass that results from the decomposition of mainly hemicellulose and to a lesser extent cellulose and lignin [6, 7].

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Downdraft gasifiers may be simple in design, but the chemical and technical processes occurring inside them are quite complicated and still not completely understood. There is absolutely no difficulty in having gasification to occur in downdraft systems but to optimally execute the process with high efficiency and high syngas quality remains an issue yet to be addressed as the basic principles underlying its design process are still completely vague, and never described quantitatively, hence the many gasifier designs and different approaches to the designs. Nonetheless, gasifier performance and syngas quality (parameters that reflects gasification process efficiency) are affected by fuel characteristics such as feed size; gasifier design parameters such as throat angle and throat diameter as well as gasifier operating variables such as temperature and feed input [8, 9]. Thus, it was considered necessary to investigate the parameters that would influence gasification process efficiency of a particular biomass material under various gasifier design and operating variables.

Gasification relies on partial oxidation at high temperatures to convert biomass into energy [10]. Many different types of gasifiers have been proposed and used for the conversion of biomass to energy, with each type designed according to feedstock characteristics. However, the difference in the types of gasifiers is linked to how the feedstock is introduced into the gasifier [11]. The most commonly used types are the fixed bed, the entrained flow and the fluidized bed gasifiers. The downdraft gasifier (which is a fixed bed type of gasifier) is the focus of this study, so the fundamental chemical kinetics of each gasification technology based on the operation of the downdraft gasifier are described, with emphasis on the four main processes (drying, pyrolysis, oxidation and reduction) occurring in the gasifier. Each of these processes is characterized by its own energy requirements, which can be endothermic or exothermic, with heat and mass transfers as well as the chemical kinetics of the reactions and pore diffusion being the main rate controlling mechanisms involved in the processes. The mechanisms of heat and mass flows vary in magnitude according to the physical and chemical processes characterized by each zone, which includes temperature, air moisture, heat losses as well as mass flow rate of air and gas including solid phases, feed rate and feed size together with biomass moisture content [8].

The study therefore aims to conduct torrefaction of a particular biomass material and determine the solid yield of the torrefied biomass as well as characterize the torrefied biomass in relation to proximate and ultimate analyses as well as in relation to calorific value including conducting the gasification process of the torrefied material using computer simulation in order to establish parameters that would impact on gasification process efficiency.

## 2. Materials and Methods

The biomass used for this study was sugarcane bagasse that was obtained from a local sugar mill in South Africa. Its torrefaction was undertaken at 250 °C in an electric muffle furnace connected to a nitrogen gas supply system, while its gasification process relied on computer simulation using a model developed by Chen et al. [12], and modified by Jayah et al. [8].

### *2.1 Experimental Set Up for Torrefaction of Bagasse*

15 g of sugarcane bagasse was weighed and placed inside a sample holder embedded in a tubular reactor that is designed to fit inside of a furnace that had been preheated to a set temperature. Fig. 1 shows the experimental set up used during sugarcane bagasse torrefaction.

The maximum working temperature of the furnace is about 3,000 °C. The torrefaction experiment was started at room temperature and was stopped soon after a temperature of 250 °C was reached. The time allowed for the material to remain in the furnace for rapid reaction was about 5 mins. The experiment was

**Fig. 1 Experimental set up used for sugarcane bagasse torrefaction.**

repeated four times and each run took ca. 30 mins under the same experimental conditions. After the torrefcation process, condensable and non-condensable products together with liquid products were produced, which were all collected and stored for further analyses.

*2.2 Characteristics of Torrefied Sugarcane Bagasse*

Characterization of the torrefied sugarcane bagasse was conducted with various analytical instruments that are relevant to gasification in order to determine the suitability of the material for gasification as well as establish the influence of torrefied fuel characteristics on gasification efficiency under various design and operating conditions. The results obtained from the characterization process are presented in Table 3, section 3.1. These results were used to conduct computer simulation of the gasification process of the torrefied material in order to establish the influence of torrefaction not just on the characteristics of the material but also on gasification process efficiency under various gasifier design and operating conditions.

*2.3 Gasification of Torrefied Sugarcane Bagasse*

As previously mentioned, the gasification process of torrefied sugarcane bagasse relied on computer simulation, which was performed with a software programme specifically designed for downdraft gasifiers to evaluate the influence of design and operating variables on the operation of the gasifier. Detailed description of the gasification simulation programme is presented in a previous publication [10]. The parameters used during gasification simulation process of torrefied sugarcane bagasse are presented in Table 1.

Some of these parameters were varied in order to determine conditions that would result in optimum gasification efficiency. The parameters varied included throat angle, throat diameter and temperature of input air as well as feed input and fuel characteristics such as feed size. These parameters are considered the most critical operating parameters that affect gasifier performance [14]. Table 2 presents the parameters that were varied during gasification simulation and their range of variation.

## 3. Results and Discussion

*3.1 Torrefied Sugarcane Bagasse Characteristics*

Gasifier performance, syngas quality as well as the heat and mass flow reactions previously described are

**Table 1 Parameters used during gasification simulation of torrefied bagasse.**

| Fuel properties | Value | Standard gasifier operating conditions [13] | Value |
|---|---|---|---|
| Carbon (%) | 56.16 | Throat diameter (cm) | 25.5 |
| Hydrogen (%) | 3.94 | Throat angle (°) | 90 |
| Oxygen (%) | 37.27 | Insulation thickness (cm) | 17.5 |
| Nitrogen (%) | 1.80 | Thermal conductivity (W/cm K) | 2.8 |
| Fixed carbon (%) | 28.45 | Temperature of input air (K) | 300 |
| Bulk density (g/cm$^3$) | 0.178 | Air input (kg/hr) | 44.5 |
| Feed size (cm) | 14.30 | Heat loss (%) | 12.8 |
| Moisture content (%) | 0.87 | Feed input (kg/h) | 40 |

*SB-Sugarcane bagasse.

**Table 2 Varied gasification parameters and range of variation during computer simulation.**

| Parameter | Range |
|---|---|
| Throat angle (°) | 25, 40, 90 |
| Throat diameter (cm) | 10, 30, 50 |
| Temperature of input air (°C) | 25, 40, 90 |
| Feed input (kg/h) | 40, 80, 100 |
| Feed size (cm) | 6, 20, 30 |

**Table 3 Measured key characteristics of torrefied sugarcane bagasse.**

| | |
|---|---|
| Proximate analysis (wt. %) | |
| Moisture content | 0.87 |
| Volatile matter content | 54.07 |
| Fixed carbon | 28.45 |
| Ash | 16.61 |
| Ultimate analysis (wt. %) | |
| C | 56.16 |
| H | 3.94 |
| O | 37.27 |
| N | 1.80 |
| O-C molar ratio | 0.66 |
| H-C molar ratio | 0.07 |
| Other properties | |
| Calorific value (MJ/kg) | 20.19 |

*$O_2$ concentration was calculated by difference, while O-C and H-C molar ratios were evaluated by taking the percentage of C, H and O, and dividing by the atomic weight of each element to give % molar mass, then dividing the minimum value by the maximum to get the global minimum value, and the maximum value by the minimum to get the global maximum value. The values presented are where possible, on a dry matter basis.

all affected by fuel characteristics, gasifier design and operating variables [8, 9, 15, 16]. Table 3 shows measured key characteristics of torrefied sugarcane bagasse.

The standard analyses error for the proximate and ultimate analyses data of torrefied sugarcane bagasse was between 0.5 and 1%, while that of its energy value was 0.4 MJ/kg. However, in terms of the proximate analysis data presented in Table 3, torrefied sugarcane bagasse exhibits low moisture content that stem from drying before analysis. For effective and efficient gasification, fuel moisture content of around 5% is desirable because high moisture content leads to incomplete combustion that creates technical hitches, which may contribute to reduction in gasification efficiency [17]. High volatile matter content was also recorded for torrefied sugarcane bagasse, which was due to minimal depletion of hemicellulose as a consequence of the low temperature (250 °C) under which torrefaction was undertaken. Fuel with high volatile matter content is desirable for gasification. Increased fixed carbon content was also measured for torrefied sugarcane bagasse, a condition that also leads to improved gasification in terms of efficiency [10]. The composition of ash was relatively high as can be observed from Table 3. This high ash composition was due to increasing inorganic elements (such as K, Mg and Ca) caused by concentration effect that was attributed to mass loss during torrefaction. These elements are major contributors to the ash content of biomass materials; biomass ash composition beyond 6% is undesirable for gasification as it would create technical challenges ranging from agglomeration, fouling and sintering that may also reduce the efficiency of the gasification process [17, 18].

On the basis of the elemental composition of torrefied sugarcane bagasse presented in Table 3, it can be seen that the material is characterized by high oxygen content that is surpassed by its content of carbon, which makes the torrefied material a suitable feedstock for gasification [4]. Its hydrogen composition is ca. 4%, which implies that moisture would be made available via hydrogen for the water-gas shift reaction to take place as this is the major reaction that leads to syngas formation during gasification [10]. The low nitrogen content measured implies low formation of NOx, which poses no environmental threats during gasification. However, one of the main environmental effects of combustion of biomass is caused by the emission of NOx, which increases with increasing biomass nitrogen content [19, 20]. The low oxygen-carbon and hydrogen-carbon ratios reported in Table 3 led to improved gasification in terms of efficiency. According to Prins et al. [21], low oxygen-carbon and hydrogen-carbon ratios raise gasification process efficiency.

A 20 MJ/kg of calorific value was measured for torrefied sugarcane bagasse, which is high enough to allude that the gasification of the material may experience increased efficiency because gasification efficiency, among other factors, is based on the energy content of the feedstock [10]. The reason for the high calorific value obtained may be attributed to alteration in chemical properties caused by torrefaction, especially with regards to the reduced oxygen-carbon and hydrogen-carbon ratios. Low oxygen-carbon and hydrogen-carbon ratios of biomass will increase calorific value and will lead to improved gasification characteristics of the biomass in terms of efficiency [21, 22].

### *3.2 Influence of Feed Size on Gasification Efficiency*

Feedstock size is a significant characteristic in any gasification process and system design as it has important influence on the burning properties of the biomass because it affects heating and drying rates during gasification [23, 24]. The influence of varied feed size on gasification process efficiency of torrefied sugarcane bagasse is presented in Fig. 2. This was obtained after computer simulation of the gasification process using the parameters presented in Tables 1 and 2, respectively.

From Fig. 2, it is evident that optimum gasification efficiency was achieved with the smallest feed size of 6 cm, a condition attributed to surface area and pore size because smaller feed sizes have larger surface areas per unit mass as well as larger pore sizes that facilitate faster rates of heat transfer and gasification [25]. However, because of alterations in the characteristics of the biomass caused by torrefaction, a high and uniform gasification temperature was achieved in the oxidation and reduction zones of the gasifier during simulation, which facilitated tar cracking and increased syngas yield, implying that fuel characteristics, in particular, size of the feedstock, are consequential to successful operation of a gasification system as supported by Xue et al. [9].

### *3.3 Influence of Feed Input on Gasification Efficiency*

When biomass feed input is increased during gasification, the process leads to improved production capacity; however, when feed input is excessively increased, it also leads to higher gas yield that may result in low gas quality created by increased tar yield [26]. The influence of varied feed input on gasification efficiency during torrefied sugarcane bagasse gasification is presented in Fig. 3.

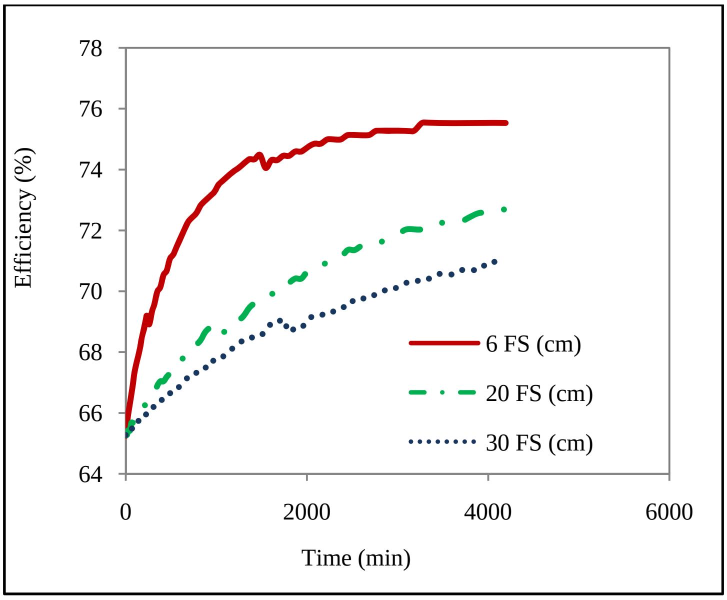


**Fig. 2 Influence of varied feed size on gasification efficiency.**

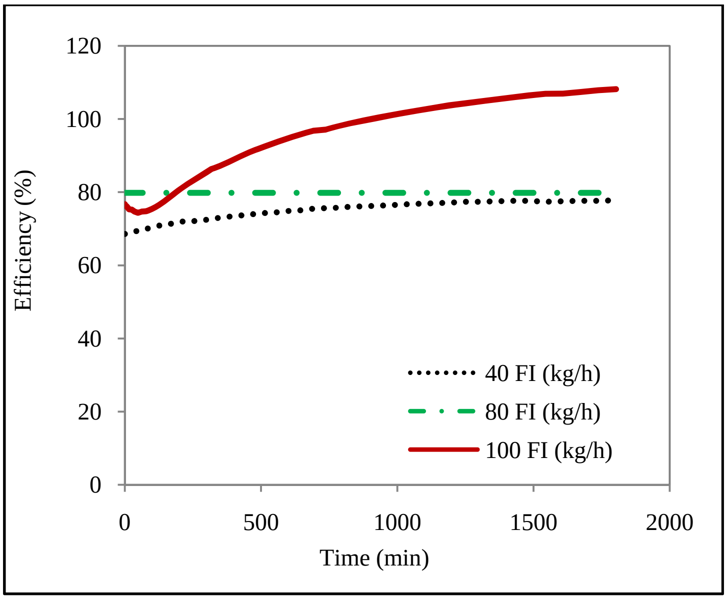


**Fig. 3 Influence of varied feed input on gasification efficiency.**

Again, from Fig. 3, optimum gasification efficiency was achieved with the highest feed input of 100 kg/h, which was attributed to increased temperatures within the gasifier during gasification simulation. A high value of biomass feed input will speed up the rate of reactions within the gasifier, especially with regard to the strong oxidation reactions, leading to increased gasification efficiency as a consequence of rise in temperature created by the oxidation reactions [27]. The increased temperature and rate of reactions created a situation with improved carbon monoxide and hydrogen production that led to complete conversion of torrefied sugarcane bagasse, at the same time decreasing char yield.

Torrefaction leads to breakage in the amorphous and crystalline regions of biomass, which indicates improved characteristics of the torrefied biomass that makes it more amenable to gasification [28-30].

### *3.4 Influence of Temperature of Input Air on Gasification Efficiency*

During gasification, temperature of input air to the gasifier functions to aid combustion so as to provide energy that is required for gasification as well as start partial oxidation of the elements contained in the feedstock; the composition of the syngas and its yield are a function of the operating temperature of the gasifier as the reactions taking place within the gasifier are temperature dependent, and downdraft gasifiers are generally operated at ambient air temperatures of about 27 °C [8, 31]. Fig. 4 shows the influence of varied temperature of input air on gasification process efficiency of torrefied sugarcane bagasse. Other variables remained the same as temperature of input air was varied between 27, 627 and 1,227 °C, respectively.

It is quite evident from Fig. 4 that gasification efficiency increased with increasing temperature of input air. This was attributed to the additional enthalpy provided by hot air for the gasification reactions to thrive. Gasification efficiency increased from about 64% to ca. 70% when the temperature of input air was raised from 27 to 627 °C, reaching a maximum of ca. 75% when it was raised to 1,227 °C. The fact that the hydrophobic properties of sugarcane bagasse improved as a result of its reduced moisture content upon torrefaction was also a contributing factor to the optimum gasification efficiency achieved. Torrefaction reduces the –OH groups contained in the structure of biomass and leads to increased torrefied biomass hydrophobic characteristics that make the material more susceptible to igniting faster, thereby

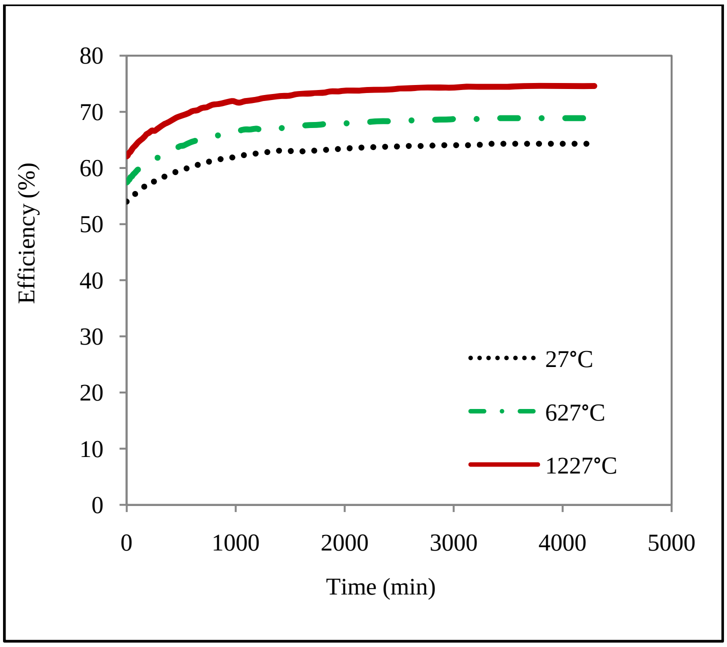


**Fig. 4 Influence of varied temperature of input air on gasification efficiency.**

allowing heat to easily spread over the entire gasifier area by convection [16, 32]. High temperature of input air is conducive to the production of a gas rich in carbon monoxide and hydrogen with increased heating value, a condition that translates into high gasification efficiency during gasification [26, 33].

### *3.5 Influence of Throat Angle on Gasification Efficiency*

The throat in downdraft gasifiers are remarkable distinctive features of the system with huge impact on gasification process efficiency because of the significance around its main function, which is even heat distribution in and around the oxidation zone of the gasifier and consequently down the reduction zone; this heat distribution is important for optimum efficiency [34-36]. Fig. 4 also shows the influence of varied throat angle on the efficiency of the gasification process of torrefied sugarcane bagasse obtained after computer simulation using the parameters presented in Tables 1 and 2.

In contrast to the results previously presented, gasification efficiency decreased with increasing throat angle according to the plot in Fig. 4, a condition attributed to the effect of divergence as a consequence of increase in reaction temperature and reaction rate. A maximum efficiency of about 75% was achieved with the smallest TA (throat angle) of 25° during gasification of torrefied sugarcane bagasse. This implies that gasification efficiency will increase with reduced gasifier TA as compared to the use of gasifiers having larger TA. The feed size of torrefied sugarcane bagasse was also among the factors that contributed to the efficiency. Previous studies by other researchers once established a correlation between gasification efficiency, gasifier geometry such as throat angle and feedstock characteristics such as feed size [27]. Improved biomass properties will enhance its gasification efficiency when systems with constricted throat angles are used [6, 16, 36, 37].

### *3.6 Influence of Throat Diameter on Gasification Efficiency*

The main factor determining the right circumstances under which gasification takes place lies in the cross-sectional area of the gasifier that includes its throat diameter [16]. The influence of varied throat diameter on the efficiency of the gasification process of torrefied sugarcane bagasse is presented in Fig. 5.

It can be noted from Fig. 6 that optimum gasification efficiency was achieved with the smallest throat diameter of 10 cm, a reason attributed to the fact that larger throat diameters (30 and 50 cm) decrease reaction temperature and reaction rate as a result of divergence related effects. Cold spots can occur when the throat diameter of the gasifier is too large, leading to reduced gasification efficiency [16]. The maximum efficiency achieved with the smallest throat diameter during gasification of torrefied sugarcane bagasse was ca. 75%, about 10% difference compared to that preceding it. In general, there seems to be a 10% increase in efficiency when larger throat diameters are replaced with smaller ones. For example, when the 50 cm TD (throat diameter) was replaced with the 30 cm TD, during gasification simulation of torrefied sugarcane bagasse, a 10% increase in gasification efficiency was noticed. The same increase in efficiency was experienced when the 30 cm TD was replaced with the 10 cm TD.

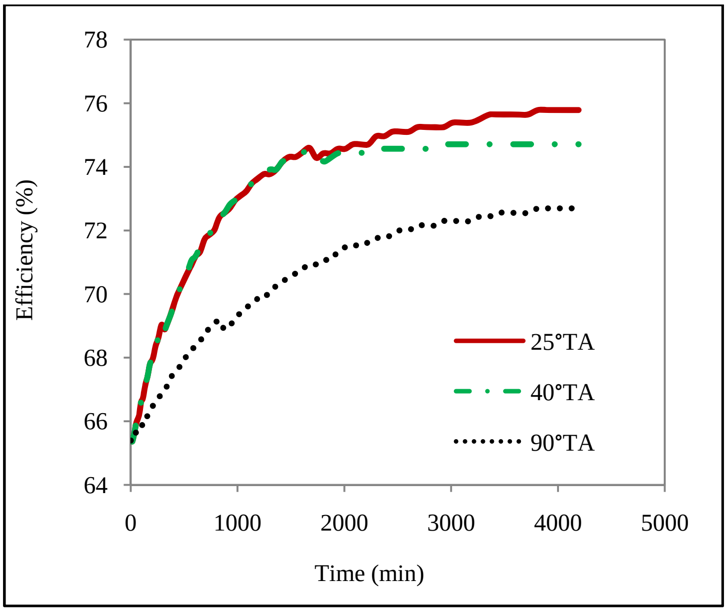


**Fig. 5 Influence of varied throat angle on the efficiency of the gasification process of torrefied sugarcane bagasse.**

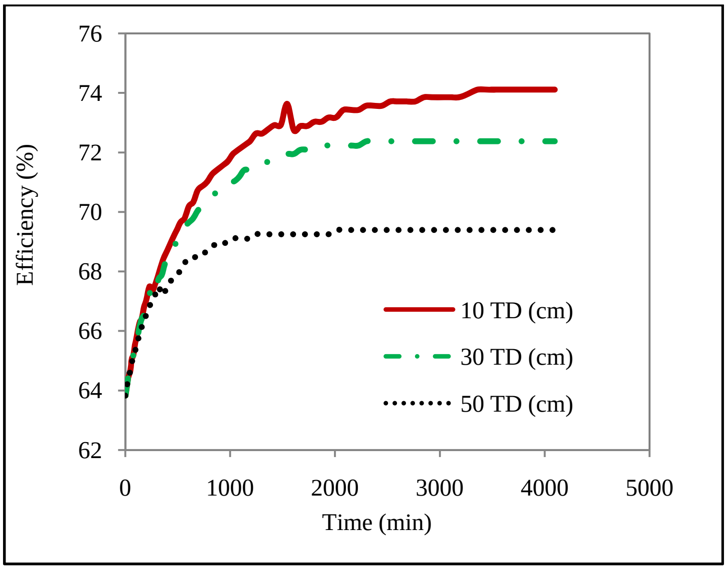


**Fig. 6 Influence of varied throat diameter on gasification efficiency.**

The functions of the oxidation zone of the downdraft gasifier were previously described, however, to accomplish these functions and for optimum gasification efficiency to be achieved, temperature distribution has to be even and cold spots avoided in this zone; one method to ensure heat is evenly distributed in the oxidation zone of the gasifier is to shrink the cross-sectional area at a certain altitude of the gasifier, in this case, the gasifier throat (both angle and diameter) [38].

## 4. Conclusions

This study investigated the influence of a specific biomass property (Feed size), gasifier design and operating conditions on gasification process efficiency and established a correlation between these properties (biomass characteristics, gasifier design and operating variables) and gasification efficiency. Considering the optimum efficiencies reached under different gasification conditions, the study established that torrefied biomass is a well suited feedstock for gasification using a downdraft system. The efficiencies reached under these conditions were high enough to deduce this fact. During the gasification simulation process, greater enhancement of combustion zone reactions was experienced, which served as a source for heat liberation that led to rise in temperatures within the gasifier. This condition also created huge tar cracking within the system, contributing to reduction in the yield of tar. However, recommended for further study is the need to employ more specialized analytical instruments to determine the amorphous and crystalline regions of torrefied biomass and their impact during gasification and make a comparison of the findings with those from previous authors.

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