



#### HIGHLIGHTS

- Heat Exchanger
- Heating Value
- Equivalence Ratio
- Gasification
- Wood Chips

## Effect of a Heat Exchanger on Syngas Quality and System Efficiency in Biomass Gasification Systems

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#### ABSTRACT

Downdraft gasifiers are pivotal in biomass gasification, converting organic materials into syngas for use as gaseous fuels and chemical feedstocks. The performance of these systems is heavily influenced by operating conditions. Since the gasification process yields high-temperature products, integrating a heat exchanger allows for the recovery of this thermal energy. This setup preheats the gasifying agent while simultaneously cooling the syngas, which facilitates easier downstream purification and eliminates the need for external heating. In this research, a counter-flow heat exchanger was fitted to the air inlet of a downdraft gasifier. This configuration extracted heat from the hot syngas to preheat the incoming air. Experiments were conducted across an equivalence ratio (ER) range of 0.15 to 0.5. With the heat exchanger, the air temperature was successfully raised from ambient levels (28.3°C–29°C) to between 60.8°C and 77°C. The results demonstrated that the concentrations of combustible gases carbon monoxide (CO), hydrogen (H<sub>2</sub>), and methane (CH<sub>4</sub>) peaked at an ER of 0.3 for both preheated and non-preheated cases. However, preheating yielded superior gas quality. At the optimal ER of 0.3, the preheated setup produced 26.75% CO, 16.24% H<sub>2</sub>, and 2.76% CH<sub>4</sub>. Without the heat exchanger, these values were lower: 26.30% CO, 13.39% H<sub>2</sub>, and 2.15% CH<sub>4</sub>. Furthermore, the lower heating value (LHV) and cold gas efficiency (CGE) showed marked improvement with preheating. The maximum LHV reached 5.1825 MJ/kg with a CGE of 64.53%, compared to 4.9435 MJ/kg and 61.56% in the ambient air setup. The study concludes that preheating the gasifying agent significantly enhances syngas quality and overall system efficiency.

**Keywords:** Heat Exchanger, Heating Value, Equivalence Ratio, Gasification, Wood Chips

## I. INTRODUCTION

There are pressing issues with energy supply, sustainability, safe operation, and efficiency as a result of the ongoing rise in global energy use. Alternative, cleaner energy sources are required due to the depletion of fossil fuels and their related environmental effects, such as local air pollution and greenhouse gas (GHG) emissions [1]. Biomass is particularly promising as it is widely available worldwide, suitable for power generation and biofuel production, and operates on a CO<sub>2</sub>-neutral basis when sustainably managed [2]. Primary biomass sources include trees, crops, and agricultural/animal wastes (IRENA, 2024) [3]. Nigeria's biomass resources remain substantial at approximately 144 million tonnes/year, comprising wood residues, agricultural wastes, and municipal biomass [4].

Biomass conversion pathways include biochemical processes (biogas, ethanol) for cogeneration and thermochemical processes—incineration, pyrolysis, and gasification—for diverse energy applications [5]. Gasification converts solid biomass into combustible syngas through partial oxidation, a technology dating back to 1920 that powered engines pre-petroleum era (Kaur *et al.*, 2025) [6]. Global energy-related CO<sub>2</sub> emissions increased by 0.8% from 2023 to 37.8 Gt in 2024 [1].

Despite the advantages of biomass gasification, small-scale downdraft gasifiers often produce high-temperature syngas with significant tar content, which reduces engine volumetric efficiency, increases maintenance demands, and lowers overall system efficiency. Moreover, a considerable fraction of the thermal energy in the hot syngas is typically lost to the environment instead of being recovered. Existing studies have focused mainly on operating conditions such as equivalence ratio and fuel properties, while relatively few have experimentally investigated the integration of heat exchangers for air preheating in downdraft gasifiers using locally available wood chips. This gap motivates the present study, which examines how integrating a counter-flow heat exchanger at the air inlet affects syngas quality and overall system efficiency.

Downdraft gasifiers produce syngas rich in H<sub>2</sub>, CO, and CH<sub>4</sub> from biomass, though incombustibles (N<sub>2</sub>, CO<sub>2</sub>) and contaminants (tar, ash) reduce efficiency (Shamay *et al.*, 2026) [8]. Tar formation peaks below 800°C, causing engine deposits and operational issues [8]. High-temperature syngas also lowers volumetric efficiency for engine applications. Heat exchangers mitigate this by recovering waste heat to preheat gasification air, enhancing syngas quality and system efficiency [9].

A heat exchanger facilitates the transfer of thermal energy between two or more fluids at differing temperatures through convection and conduction across a separating medium. In the context of gasification, the heat exchanger serves a dual purpose: it acts as a primary treatment stage by cooling the gas for engine compatibility and provides an opportunity for heat recovery. The main objective of this work is to construct and assess the performance of a heat exchanger integrated with a downdraft gasifier. Specifically, the impacts of preheating gasifying agents to maximise the total gasification efficiency are examined.

The specific contribution of this work is threefold. First, it experimentally integrates a counter-flow heat exchanger on the air inlet of a downdraft gasifier operating with Nigerian wood chips. Second, it quantifies the effect of air preheating on syngas composition, lower heating value, and cold gas efficiency across an equivalence ratio range of 0.15–0.5. Third, it provides practical design and operational insights for improving the performance of small-scale biomass gasification systems through waste heat recovery.

## II. METHOD AND PROCEDURE

The various methods employed in this research work are presented in this section.

### 2.1 Waste collection and preparation

Wood residues were obtained from sawmills and carpentry workshops in Okada, Nigeria. In order to feed the wood waste into the gasifier, it was chopped into pieces. The prepared wood fuel supplied into the downdraft gasifier is depicted in Figure 1.1.



**Figure 1.** The fuel wood chips

2.2 Wood characterisation

Proximate and ultimate analyses were conducted to determine the moisture content, volatile matter, fixed carbon, ash, and elemental composition of the fuel. These properties are required to evaluate the suitability of the wood chips for gasification and to interpret the resulting syngas quality and energy content.

2.3 Proximate analysis

2.3.1 Determination of moisture content

The test procedure described in ASTM Standard E 871-82 was used to assess the moisture content. By weighing 0.78 g of each sample in a marked, pre-weighed petri dish and drying it at 105°C for three hours, the moisture content of the wood was calculated in triplicate. Equation (1) was used to determine the percentage moisture content as a percentage of weight loss [10]; [11]; [12]; [13].

%MC = (g - χ) / g × 100 ..... (1)

where,  
g = Sample's weight (g)  
χ = Dry matter weight and (g)

Table 1 displays the experimental data used to calculate the wood fuel's moisture content.

Table 1. Experimental data of moisture content

| Parameters            | Fuel wood |
|-----------------------|-----------|
| Weight of samples (g) | 0.780     |
| dry matter weight (x) | 0.682     |
| Weight loss (g-x)     | 0.098     |

%MC = (0.78 - 0.682) / 0.78 × 100 = 12.56% ..... (2)

2.3.2 Determination of Volatile Matter

By weighing 0.156g of each sample in a crucible, covering it with a lid, and heating it to 550°C for ten minutes in a muffle furnace before cooling it in a desiccator, the volatile matter of the fuel wood was measured in triplicate. Equation [3] was used to determine the percentage of volatile matter [14]; [15]; [16]; [17].

%VM = (χ - y) / g × 100 ..... (3)

where,  
g = Sample's weight (g)  
χ = Dry matter weight (g)  
y = Residue weight o(g)

The results of the laboratory experiment used to determine volatile matter are displayed in Table 3.

Table 2. Experimental data of volatile matter

| Parameters               | Fuel wood |
|--------------------------|-----------|
| Weight of samples (g)    | 0.156     |
| weight of dry matter (x) | 0.136     |
| Weight of residue (y)    | 0.021     |
| Weight loss (x-y)        | 0.115     |

%VM = ((0.136 - 0.021) / 0.156) × 100 = 73.72%

2.3.3 Determination of ash content

By weighing 0.187g of the sample into a crucible and heating it to 550°C for eight hours in a muffle furnace, the ash content was ascertained in triplicate. After that, the crucible was removed from the furnace and allowed to cool in the desiccator. Equation (4) was utilised to calculate the ash content after the weight had [14]; [17]; [16]; [15].

%Ash = (χ / g) × 100 ..... (4)

where,  
g = Sample weight (g)  
χ = Ash weight of ash (g)

Table 3 shows the laboratory experimental result obtained for determination of ash content

Table 3. Experimental data of Ash content

| Parameters          | Fuel wood |
|---------------------|-----------|
| Sample's weight (g) | 0.187     |
| Weight of Ash (x)   | 0.006     |

%Ash = (0.006 / 0.187) × 100 = 3.21%

2.3.4 Percentage Fixed Carbon

According to Equation (5) [14]; [17]; [16]; [15], the percentage fixed carbon was calculated by deducting the total percentage of volatile matter (%VM), moisture content (%MC), and ash content (% Ash) from 100.

%FC = 100% - (%VM + %Ash + %MC) ..... (5)

%FC = 100% - (73.72 + 3.21 + 12.56)10.51%

2.4. Ultimate analysis

2.4.1 Determination of Carbon Content

The carbon content was determined by introducing 0.053g of the sample to a 250 cm3 conical flask using the procedure described in [17]. Following the addition of 20 cm3 of concentrated hydrogen tetraozosulphate (VI) (H2SO4) and 10 cm3 of 0.1M potassium dichromate (VII) (K2Cr2O7), the solution in the conical flask was let to cool

for about 30 minutes. After cooling, 0.5M ferrous sulphate (FeSO<sub>4</sub>) was titrated, 100 cm<sup>3</sup> of distilled water was added, and three drops of O-phenanthroline ferrous complex were added as an indicator. The carbon content was calculated using equation (2.5) [17]; [18].

$$\%C = \frac{(B-T) \times M \times 0.003 \times 100 \times 1.33}{g} \quad \dots \dots \dots (6)$$

where

B = Blank Titre

T = Sample Titre

M = molarity of the acid used =1

g is the Weight of sample (g)

Table 4 shows the laboratory experimental result data obtained for determination of carbon content

**Table 4.** Experimental data of Carbon content

| Parameters            | Fuel wood |
|-----------------------|-----------|
| Weight of samples (g) | 0.053     |
| Blank Titre (B)       | 10.400    |
| Sample Titre (T)      | 4.157     |

$$\%C = \frac{(10.4-4.157) \times 1 \times 0.003 \times 100 \times 1.33}{0.053} = 47\%$$

#### 2.4.2 Determination of Nitrogen Content

The amount of nitrogen in the sample was determined by weighing 1.003g of the sample into a Kjeldahl digestion tube. 20 cm<sup>3</sup> of H<sub>2</sub>SO<sub>4</sub> and 3g of a mixed catalyst consisting of CuSO<sub>4</sub>, Na<sub>2</sub>SO<sub>4</sub> and selenium powder was added into the tube. The tube was heated gently and boiling for about 3 hours, then allowed to cool. The cooled mixture was then diluted with 100ml of distilled water in a volumetric flask. To an aliquot (10cm<sup>3</sup>) of the digest, 10 cm<sup>3</sup> of 40% sodium hydroxide (NaOH) solution was added to the connected Kjeldahl distillation apparatus and heated to boiling. The distillate was condensed into the conical flask containing 10 cm<sup>3</sup> of 2% boric acid and 2 drops of methyl blue indicator was added and the alkaline distillate was titrated against 1M sulphuric acid. Equation (7) was used to compute the percentage nitrogen content [17]; [18].

$$\%N = \frac{(T \times M \times 0.14 \times DF)}{g} \times 100 \quad \dots \dots \dots (7)$$

where

M =molarity of the acid used =1

g =Weight of sample

T =Titre value

DF = Dillution factor diluted =0.1

Table 4 shows the laboratory experimental result data obtained for determination of nitrogen content

Table 4. Experimental data of Nitrogen content

Parameters Fuel wood

Weight of samples (g) 1.003

Titre Value (T) 0.716

$$\%N = \frac{(0.716 \times 1 \times 0.14 \times 0.1)}{1.003} \times 100 = 1.0\%$$

#### 2.4.3 Determination of Sulphur Content

The amount of sulphur in the fuel wood was computed using Equation (9) [17]; [18]. Table 5 show the experimental data obtained from the analysis of the sulphur content.

$$\%S = \frac{(\chi \times 0.1373)}{g} \times 100 \quad (8)$$

where,

g = weight of sample (g)

χ = weight of BaSO<sub>4</sub> (g)

Experimental Data of Sulphur Content

Parameters Fuel wood

Initial weight of samples (g) 1.002

Weight of BaSO<sub>4</sub> (x) 0.0073

$$\%S = \frac{(0.0073 \times 0.1373)}{1.002} \times 100 = 0.1$$

#### 2.4.4 Hydrogen content

Hydrogen content was determined using Equation (9) as seen in [17]; [18]. Table 5 show the experimental data obtained from the analysis of the hydrogen content

$$\%H = \frac{(w \times 0.1119 \times 100)}{g} \quad \dots \dots \dots (9)$$

w = weight of water (g)

g =Initial weight of pellet

**Table 5.** Experimental data of Hydrogen content of pellets

| Parameters                    | Fuel wood |
|-------------------------------|-----------|
| Initial weight of samples (g) | 0.970     |
| Weight of water               | 0.615     |

Initial weight of samples (g) 0.970

Weight of water 0.615

$$\%H = \frac{(0.615 \times 0.1119 \times 100)}{0.97} = 7.1\%$$

#### 2.4.5 Determination of oxygen content

The percentage of Oxygen content was computed by subtracting the sum of percentage composition of Carbon, Nitrogen, Sulphur, Hydrogen and the Ash content of the pellet from 100 as shown in the Equation (10) (Umar et al, 2017[17]; Fagan et al, 2011 [18]):

$$\%O = 100 - (\%C + \%H + \%N + \%S + \%Ash) \quad \dots \dots \dots 10$$

$$\%O = 100 - (47.0 + 7.1 + 1.0 + 0.1) = 44.8\%$$

#### 2.4.6 Determination of Bulk Density

Bulk density is defined as the weight per unit volume. Equation (11) was used to determine the bulk density.

$$\text{Bulk Density} = ((w-e))/V \dots\dots\dots (11)$$

e = Mass of empty dish (g)

w = Mass of empty dish+fuel wood (g)

V = Volume of a unit fuel wood (cm<sup>3</sup>)

Table 6 Experimental data obtained for bulk density

|                              |           |
|------------------------------|-----------|
| Parameters                   | Fuel wood |
| Weight of Empty (e)          | 31.00     |
| Weight of empty + sample (w) | 52.62     |
| Weight of sample (w-e)       | 21.62     |
| Volume of sample (V)         | 73.3      |

**Table 6.** Experimental data obtained for bulk density

| Parameters                   | Fuel wood |
|------------------------------|-----------|
| Weight of Empty (e)          | 31.00     |
| Weight of empty + sample (w) | 52.62     |
| Weight of sample (w-e)       | 21.62     |
| Volume of sample (V)         | 73.3      |

$$\text{Bulk Density} = \frac{21.62}{73.3} = 0.295 \text{g/cm}^3 \dots\dots\dots (12)$$

The experimental procedure for wood waste gasification was initiated by loading the reactor with 5 kg of dried wood fuel. Initial combustion was achieved by igniting a separate portion of wood using butane gas and a small amount of petrol until it reached a red-hot state, a process requiring approximately 10 to 15 minutes. Once fully ignited, these embers were transferred into the loaded gasifier, and an induced fan was engaged to supply air, sustaining the combustion for an additional 30 minutes until the main fuel bed ignited properly. At this stage, the gasifier was sealed, and the air supply was regulated to a specific mass flow rate to allow gasification to proceed through the interaction of the air and fuel for one hour. At each operating point, the air mass flow rate was adjusted to achieve the desired equivalence ratio between 0.15 and 0.5, based on the stoichiometric air requirement calculated from the fuel's ultimate analysis.

The resulting syngas was extracted from the base of the reactor via a gas exit pipe, while the byproduct ash was filtered through a perforated grate into a collector. To ensure the gas was suitable for analysis, the raw syngas underwent a multi-stage cleaning and cooling process. This involved a heat exchanger to preheat the incoming air and cool the gas, a cyclone for particulate removal, a secondary

cooler, an expansion drum to eliminate water vapor, and a final filter unit for fine gas cleaning.

The purified syngas was compressed into cylinders for characterization. Analytical evaluation of the gas was conducted using a Gas Chromatograph (Thermoquest Trace 2000GC) to determine the percentage mass composition and the total calorific value of the produced fuel. The experimental configuration integrated several key components, including the reactor, cyclone, heat exchanger, and filter unit, to facilitate efficient thermochemical conversion.



**Figure 2.** Gasification experimental set-up [1-Cyclone, 2-Cooler, 3-Induced fan, 4-Heat Exchanger, 5-Reactor, 6-Burner, 7-Expansion drum, 8-Ash pond, 9-Filter unit]



**Figure 3.** Flaring of syngas in the burner

#### 2.4.7 Synthesis gas analysis using chromatograph

*thermoquest trace 2000GC*

A gas-tight syringe was used to inject 0.3 cm<sup>3</sup> of gas at a carrier gas rate of 1 ml/min into the ThermoQuest Trace 2000 GC's Elite analytical column. Each operating condition was tested at least twice, and the reported gas compositions, LHV, and CGE values represent the average of these repeated measurements.

The components were separated on a 30-meter-long, 0.25-micrometer-diameter column filled with polymer. In the low sensitivity mode, the column was used to measure the amount of vapour, methane, carbon dioxide, and carbon monoxide; in the high sensitivity mode, it was used to measure the amount of steam and hydrogen.

Isothermal conditions were used for the separation. The readout used the correlation between the detector response and retention time to create chromatographs of the syngas under analysis. The Gas Chromatograph Thermoquest Trace 2000GC apparatus used for the gas analysis is seen in Figure 3.5. The test settings for the syngas analysis utilising the Gas Chromatograph Thermoquest Trace 2000GC equipment are displayed in Table 7.



**Figure 4.** Gas Chromatograph thermoquest trace 2000GC

**Table 7.** Thermoquest trace 2000 GC/MS conditions

| Analytical Column | Elite -5ms(30m x 25mm x 0.25um) |
|-------------------|---------------------------------|
| Injection Port    | Programmable Split/Splitless    |
| Type              |                                 |
| Injector          | 280°C                           |
| Temperature       |                                 |
| Injection Type    | Split(25ml/min)                 |
| Syringe           | 5UI                             |
| Volume            |                                 |
| Injection         | 1UI                             |
| Volume            |                                 |
| Injection         | Normal                          |
| Speed             |                                 |

|               |                    |          |
|---------------|--------------------|----------|
| Rinse Solvent | Methylene Chloride |          |
| Carrier Gas   | Helium             |          |
| Type          |                    |          |
| Carrier Gas   | Flow 1ml/min       |          |
| Program       |                    |          |
| Hold Time     | 0.5min             | Hold     |
| Oven          | 100°C              | 260°C    |
| Temperature   |                    |          |
| Hold Time     | 0min               | 0min     |
| Rate          | 8°C/min            | 35°C/min |

## 2.5 The heat exchanger performance analysis

The performance of the counter-flow heat exchanger was evaluated by measuring air inlet and outlet temperatures, syngas inlet and outlet temperatures, and calculating effectiveness and heat recovery rates. These measurements were used to quantify the contribution of air preheating to syngas quality and cold gas efficiency.

A Double Pipe Heat Exchanger was employed in this research. It is regarded as one of the simplest types of tubular heat exchanger. It is made up of concentric pipes that are separated by mechanical closures. Double pipe heat exchangers are relatively cheap to construct and require minimal maintenance. They are used in high temperature and high pressure applications for sensible heating or cooling (Marzouk *et al.*, 2023) [19]. In recent years, several studies have been carried out to evaluate and improve the performance of heat exchangers in general. High performance heat exchangers are required in order to increase the efficiency of most industrial applications where heat exchangers are of great necessity. A recent study described the principle techniques involved in augmentation of single phase heat transfer in a double pipe heat exchanger.

The use of heat exchanger enhances the efficiency of a system or process. The performance of a heat exchanger is measured using important thermal parameters which include quantity of heat, also known as heat duty; overall heat transfer coefficient; log mean temperature difference (LMTD); effectiveness; and capacity ratio.

The quantity of heat emitted by the syngas and absorbed by the air was determined using Equation (12) and (13) respectively as seen in Nwokolo *et al.*, 2020.

$$Q_e = (mC_p)_h (T_{h,i} - T_{h,o}) \quad \text{..... (13)}$$

$$Q_c = (mC_p)_c (T_{c,o} - T_{c,i}) \quad \text{..... (14)}$$

Where  $m_c$  and  $m_h$  are the mass flow rate of air and

syngas respectively;  $C_{p,c}$  and  $C_{p,h}$  are the specific heat capacity of syngas and air respectively;  $T_{c,i}$  and  $T_{h,i}$  are the inlet temperature of syngas and air, respectively; and  $T_{h,o}$  and  $T_{c,o}$  are the outlet temperature of syngas and air respectively.

According to Nwokolo et al. (2020) [20], Equation (15) defines the overall heat transfer coefficient ( $U$ ), a crucial performance metric.

$$U = \frac{Q_e}{A \times LMTD} \dots\dots\dots(15)$$

where  $A$  is the heat transfer surface area and  $LMTD$  is the log mean temperature difference which is defined as shown in Equation (16) for counterflow configuration as seen in Tali et al, (2017) [21].

$$LMTD = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\left(\frac{(T_{h,i} - T_{c,o})}{(T_{h,o} - T_{c,i})}\right)} \dots\dots\dots(16)$$

The effectiveness ( $S$ ) was determined using Equation (17) as seen in [21].

$$S = \frac{C_{max}(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})} \dots\dots\dots(17)$$

where  $C_{max}$  and  $C_{min}$  stand for the fluids' maximum and minimum capacity coefficients, respectively. The mass flow rate multiplied by the fluids' specific heat capacity yields the capacity coefficients.

The specific heat capacities can be computed using Equation (18) as seen in [22].

$$C_p = \sum_i \frac{n_i}{n_m} C_{p,i} \dots\dots\dots(18)$$

Where:

$mm_i$  = mass fraction of spSecie i

Specific heat capacities values of some common syngas yield specie are given in Table 8 as seen in engineering tool box [23].

**Table 8.** Specific heat capacities values of some common syngas yield species

| Sp<br>ecie                                   | A<br>ir  | C<br>O   | C<br>H <sub>4</sub> | H <sub>2</sub> | N <sub>2</sub> | C<br>O <sub>2</sub> | H <sub>2</sub> O |
|----------------------------------------------|----------|----------|---------------------|----------------|----------------|---------------------|------------------|
| Specific<br>Heat<br>Capacity<br>(kJ/kg<br>K) | 1<br>.01 | 1<br>.02 | 2<br>.22            | 1<br>4.32      | 1<br>.04       | 0.<br>844           | 1<br>.93         |

To assess reproducibility, each operating condition in the test matrix (defined by inlet temperatures and flow rates on both sides) was repeated at least three times on different days. For each run, data were recorded over a period of 20

minutes after verifying that steady-state conditions had been reached, defined as variations in inlet and outlet temperatures below  $\pm 0.2$  °C and flow-rate fluctuations below  $\pm 1\%$  of the mean. The run-to-run variation of the overall heat-transfer coefficient remained within  $\pm 4\%$ , and the variation of effectiveness within  $\pm 5\%$  for all tested points, indicating good experimental repeatability.

In this study, the heat-recovery unit was configured as a double-pipe counter-flow heat exchanger, consisting of concentric carbon-steel pipes with an inner tube diameter of 25 mm, an outer tube diameter of 33 mm, and an effective heat-transfer length of 1.5 m. The hot syngas flowed through the inner tube, while the combustion air passed through the annulus in counter-current arrangement, yielding a total heat-transfer surface area of 0.12 m<sup>2</sup>. All joints were fully welded to minimise leakage, and the assembly was externally insulated with 50-mm-thick mineral wool to reduce ambient heat losses.

## 2.6 Performance evaluation of the gasifier

The Cold Gas Efficiency and Lower Heating Value of the syngas produced were evaluated.

### 2.6.1 Cold Gas Efficiency

According to [11], Cold Gas Efficiency (CGE) is calculated for each test condition by dividing the output energy (heating value of the syngas) by the input energy (heating value of the biomass) using Equation (19).

$$CGE = \frac{LHV_{syngas} \times Y_{syngas}}{m_{biomass} \times LHV_{biomass}} \times 100 \dots\dots\dots(19)$$

where:

$LHV_{syngas}$  and  $LHV_{biomass}$  = Lower heating value of the syngas and biomass respectively,

$Y_{syngas}$  = mass flow rate of the syngas in kg/s = 0.002406kg/s

$m_{syngas}$  = mass flow rate of the biomass in kg/s = 5kg/hr = 0.001389kg/s

$LHV_{biomass}$  = 15.74MJ/kg

At ER 0.3 with HE

$$CGE = \frac{5.1825 \times 0.002406}{0.001389 \times 15.74} \times 100 = 57.04\%$$

Correction factor =  $LHV / HHV$

$$= \frac{15.74}{17.1883} = 0.9158$$

### 2.6.2 Lower heating value

The total of the standard lower heating values of the combustible gases in the syngas produced is used to calculate the syngas's lower heating value. Equation (20) provides a mathematical expression for this.

$$LHV_{syngas} = \sum(LHV_i \times mm_i) \dots\dots\dots (20)$$

where:

$mm_i$  = mass fraction of specie i

Lower heating values of some common syngas yield specie are given in Table 9 as seen in engineering tool box [23].

**Table 9.** Lower heating values of some common syngas yield species

| Specie                      | CO     | CH <sub>4</sub> | H <sub>2</sub> | C <sub>2</sub> H <sub>4</sub> |
|-----------------------------|--------|-----------------|----------------|-------------------------------|
| Lower heating value (MJ/kg) | 10.112 | 50              | 120            | 47.195                        |

### III. FINDINGS AND DISCUSSION

This section presents the results obtained from the experimental and analytical investigations conducted in this study. The findings are systematically discussed in relation to the physicochemical characterization of the fuel wood, the performance evaluation of the gasification system, and the quality assessment of the syngas produced. The results are interpreted within the context of existing literature to establish the scientific merit and practical relevance of the outcomes. Each subsection provides a detailed analysis of the data, highlighting key trends, comparisons, and implications for sustainable biomass energy utilization.

#### 3.1 Characterization of fuel wood

Proximate and ultimate analyses were conducted to determine the key physicochemical properties of the fuel wood used in the downdraft gasifier. The proximate analysis showed a moisture content of 12.56%, which lies within the typical desirable range of 8–18% for biomass gasification and ensures that excessive energy is not consumed in evaporating water during combustion. Maintaining moisture in this range helps to avoid excessive participation of water in water–gas shift reactions that would otherwise lower the overall reaction temperature and reduce the yield of combustible gases.

The volatile matter content was 73.72%, indicating that a substantial fraction of the biomass decomposes into volatile gases upon heating, which is beneficial for ignition and for producing a syngas rich in combustible components. The fixed carbon content was 10.51%, while ash content

was 3.21%, both of which are favourable for gasification. An ash content below about 5% is particularly important to minimise clinker formation and slagging in the reactor, thereby supporting stable operation over extended periods.

The ultimate analysis determined the elemental composition of the fuel wood to be 47 wt% carbon, 7.1 wt% hydrogen, 44.8 wt% oxygen, 1.0 wt% nitrogen, and 0.1 wt% sulphur. These values were used to derive a generalised empirical formula for the fuel wood of  $C_{3.917}H_{7.1}O_{2.8}N_{0.0714}S_{0.0031}$ , which is consistent with typical hardwood-type biomass reported in the literature. The very low sulphur content is advantageous because it reduces the potential for sulphur oxide formation and subsequent corrosion in downstream components such as chimneys and heat exchangers. The distribution of the elemental mass fractions is illustrated in Figure 3.1, which shows that carbon and oxygen dominate the composition, with smaller contributions from hydrogen and trace elements.

Using the proximate analysis data, the higher heating value (HHV) of the fuel wood was estimated by an established correlation, yielding 17.1883 MJ/kg. The corresponding lower heating value (LHV), obtained by accounting for latent heat losses due to moisture and hydrogen content, was 15.744 MJ/kg. These values are comparable to those reported for other common biomass feedstocks such as corn cob, palm kernel shell, and birchwood, indicating that the selected fuel wood provides a competitive energy density for gasification applications. Overall, the combination of moderate moisture content, high volatile matter, low ash, low sulphur, and a relatively high LHV confirms that the fuel wood is well suited for downdraft gasification and supports the performance results obtained in the subsequent gasification experiments.

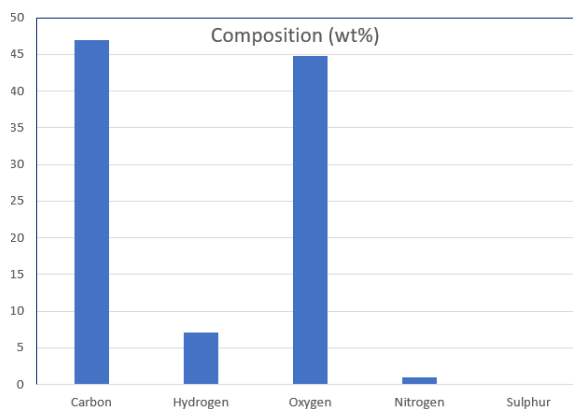


**Figure 5:** Ultimate analysis of fuel wood

### 3.2 Chemical formula of the fuel wood

The generalised empirical formula of the fuel wood was determined from the ultimate analysis results. For solid biomass, the fuel can be represented as  $C_vH_wO_xN_yS_z$ , where the subscripts  $v$ ,  $w$ ,  $x$ ,  $y$ , and  $z$  denote the number of moles of carbon, hydrogen, oxygen, nitrogen, and sulphur, respectively. The mass fractions obtained from the ultimate analysis were 47 wt% carbon, 7.1 wt% hydrogen, 44.8 wt% oxygen, 1.0 wt% nitrogen, and 0.1 wt% sulphur (Barman et al., 2012) [24].

To convert these mass percentages to molar quantities, each element's mass fraction was divided by its atomic weight:

$$C = 47\text{wt}\%, v = \frac{47}{12} = 3.917$$

$$H = 7.1\text{wt}\%, w = \frac{7.1}{1} = 7.1$$

$$O = 44.8\text{wt}\%, x = \frac{44.8}{16} = 2.8$$

$$N = 1.0\text{wt}\%, y = \frac{1.0}{14} = 0.071429$$

$$S = 0.1\text{wt}\%, z = \frac{0.1}{32} = 0.003125$$

On this basis, the empirical formula of the fuel wood can be written as:

$$= C_{3.917}H_{7.1}O_{2.8}N_{0.071429}S_{0.003125}$$

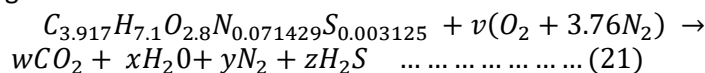
This empirical formula is consistent with typical hardwood-type biomass reported in the literature and is used as the basis for subsequent stoichiometric calculations of the air–fuel ratio and gasification reactions in the analysis of the gasifier performance.

### 3.3 Gasification experimental result analysis

The gasification experiments were conducted using the characterised fuel wood and the empirical formula, which served as the basis for stoichiometric calculations. The overall combustion–gasification reaction was written in terms of this formula and a generalised amount of oxidant, allowing the stoichiometric air–fuel ratio and mass flow rates to be determined. The stoichiometric air requirement was calculated using established correlations, and the actual air supply was adjusted to achieve equivalence ratio

(ER) values in the range 0.15–0.5. Based on a fuel mass flow rate of 0.001389 kg/s (corresponding to 5 kg loaded into the reactor over the experimental period), the required air mass flow rates for each ER were obtained and are summarised in Table 9.

Using the elemental composition of the fuel wood, the global reaction of the form.



was balanced to determine the stoichiometric coefficients. Carbon, sulphur, hydrogen, and oxygen balances were applied sequentially to obtain the values of  $v$ ,  $w$ ,  $x$ ,  $y$ , and  $z$  and to compute the required moles of oxygen and nitrogen supplied by the air. These stoichiometric relationships formed the basis for estimating the theoretical air requirement and for setting the experimental air flow rates corresponding to the selected ER values.

The mass fractions of major syngas components ( $CO$ ,  $H_2$ ,  $CH_4$ ,  $CO_2$ ,  $N_2$ ) as functions of ER were determined from the gas chromatograph analysis and are presented in Figures 3.2 and 3.3 for the cases with and without air preheating, respectively. In both configurations, the mass fractions of the combustible gases  $CO$ ,  $H_2$ , and  $CH_4$  reached their maximum values at an ER of approximately 0.30. Deviations from this ER, either lower or higher, resulted in reduced combustible gas fractions. At ER values below 0.30, the limited oxidant supply led to incomplete conversion and lower gasification temperatures, reducing the formation of  $CO$  and  $H_2$ . At ER values above 0.30, the increased air supply promoted further oxidation of  $CO$  and  $H_2$  to  $CO_2$  and  $H_2O$ , increasing the  $N_2$  and  $CO_2$  fractions and thereby diluting the syngas and lowering its calorific value.

The trends observed here are consistent with typical downdraft gasifier behaviour, where an intermediate ER yields the best trade-off between sufficient oxidant for high temperatures and avoidance of excessive oxidation of combustible species. Similar patterns have been reported in studies using other biomass feedstocks; for example, when rice husk was gasified over an ER range of approximately 0.17–0.30, the maximum fractions of  $CO$ ,  $H_2$ , and  $CH_4$  were found at an intermediate ER, while  $CO_2$  was minimised at that point. In the present work, the identification of  $ER = 0.30$  as the optimum operating point provides a basis for selecting operating conditions that maximise syngas quality and supports the subsequent analysis of lower heating value and cold gas efficiency under both preheated and non-preheated air conditions.

Equation (21) was used to calculate the stoichiometric air-fuel ratio, as shown in [28] and [29]. Equation (21) was used to calculate the mass flow rate of air to provide an equivalency ratio variation between 0.2 and 0.5 using the mass flow rate of fuel wood as 5 kg/s (0.001389 kg/s)

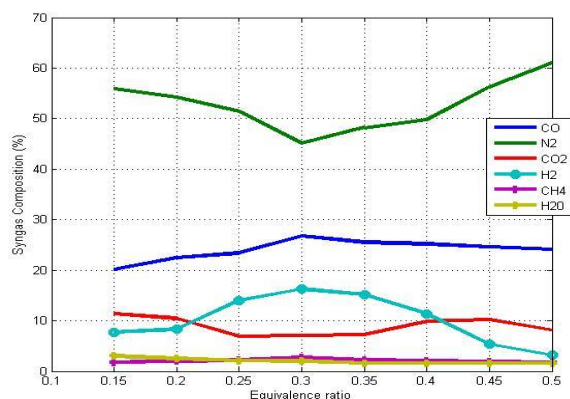


**Figure 6:** Mass fraction of syngas using heat exchanger to preheat gasifying agent

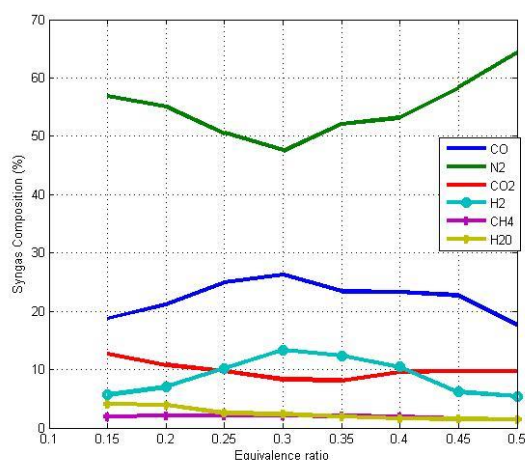


**Figure 7:** Mass fraction of syngas without using heat exchanger to preheat gasifying agent

The plot of the species mass fraction at various equivalency ratios utilising a heat exchanger to preheat the gasifying agent is shown in Figures 4.3 and 2.4, respectively. According to the findings, the percentage mass fraction of the combustible gases CO, CH<sub>4</sub>, and H<sub>2</sub> reaches it's highest when the equivalency ratio is 0.30 in both situations where the gasifying agent is preheated using a heat exchanger and when it is not. In both scenarios, the flammable gas compositions are reduced by further increasing or decreasing the equivalency ratio from 0.30.

Excessive feedstock combustion, an increase in N<sub>2</sub> composition, a drop in CO composition, an increase in CO<sub>2</sub> output, and other consequences result from an equivalency ratio increase above 0.30. The heating value of the syngas will undoubtedly decrease as a result. According to a study by [30], which used rice husk as fuel and varied the

equivalency ratio from 0.169 to 0.3, showed a similar pattern. Their combustible gases (CO, H<sub>2</sub>, and CH<sub>4</sub>) reached their maximum value at an equivalency ratio of 0.21. Additionally, CO<sub>2</sub> was seen to be at its lowest at the equivalency ratio.

### 3.4 Lower Heating Value of Syngas

The lower heating values (LHV) and cold gas efficiencies (CGE) of the syngas under the different test conditions were determined from the measured gas compositions and are summarised in Figure 3.4. The variation of LHV with equivalence ratio (ER) for both preheated and non-preheated gasifying air is illustrated in Figure 4.5. For the case where the gasifying agent was preheated using the heat exchanger, the LHV of the produced syngas ranged from 1.58 MJ/kg to 5.1825 MJ/kg over the ER range of 0.15–0.5, with a maximum value of 5.1825 MJ/kg at ER = 0.30. In contrast, when the gasifying agent was not preheated, the LHV ranged from 2.2411 MJ/kg to 4.9435 MJ/kg, with the maximum value of 4.9435 MJ/kg also occurring at ER = 0.30.

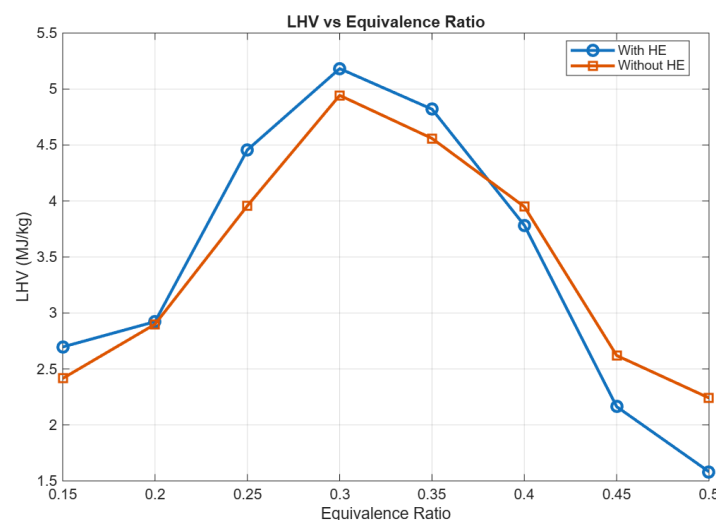


**Figure 8:** Lower heating value of syngas

These results show that air preheating consistently increased the LHV of the syngas across the investigated ER range, with the most pronounced improvement at the optimum ER. The higher LHV in the preheated configuration can be directly linked to the increased fractions of combustible gases (CO, H<sub>2</sub>, and CH<sub>4</sub>) observed in the gas composition analysis. As the contribution of these species to the energy content of the syngas is substantial, even modest increases in their mass fractions translate into noticeable gains in LHV. The enhancement in LHV is therefore a direct consequence of the improved thermochemical environment created by preheating the gasifying air, which raises reaction temperatures and promotes conversion of the solid fuel into energy-rich gaseous products.

The associated cold gas efficiency values follow a similar pattern, with the preheated configuration exhibiting higher CGE than the non-preheated case at corresponding ER values. This indicates that a larger fraction of the chemical energy in the fuel wood is captured in the syngas when the gasifying agent is preheated. Together, the LHV and CGE results confirm that integrating a heat exchanger to recover waste heat from the syngas and use it for air preheating is an effective strategy for enhancing the overall energy performance of the downdraft gasification system.

The identification of ER = 0.3 as the optimum in this study is consistent with previous work on downdraft gasifiers, where intermediate ER values have been reported to maximise syngas calorific value and minimise tar formation. Although absolute values of LHV and gas composition differ due to variations in feedstock and reactor design, the trends observed here—peak combustible gas fractions and LHV at intermediate ER, and improved performance with enhanced thermal integration—are in agreement with these earlier findings.

### 3.5 Cold gas efficiency

Cold gas efficiency (CGE) was used to evaluate how effectively the chemical energy in the fuel wood was converted into syngas under the different test conditions. CGE was calculated as the ratio of the energy content of the produced syngas (based on its lower heating value and mass flow rate) to the energy input associated with the biomass feed, expressed as a percentage. The calculated CGE values for both preheated and non-preheated gasifying air, over the ER range of 0.15–0.5, are presented in Table 9 alongside the corresponding LHV values and are plotted in Figure 3.5. In [30] investigation, cold gas efficiency variation with equivalency ratio was found to behave similarly, with equivalency ratio values ranging from 0.169 to 0.3. But when rice husk was used as fuel, their ideal value was found to be 0.21. The CGE decreased away from this value.

The variation of CGE with ER reflects the combined influence of gas composition and conversion efficiency. At low ER values, limited oxidant supply leads to incomplete fuel conversion and lower syngas production, resulting in reduced CGE. As ER approaches 0.30, improved combustion in the oxidation zone raises the temperature and enhances gasification reactions, increasing both the quantity and quality of syngas and thus boosting CGE. Beyond ER = 0.30, additional air promotes further oxidation of combustible gases to CO<sub>2</sub> and H<sub>2</sub>O and increases nitrogen dilution, which lowers both the LHV and the fraction of fuel energy captured in the syngas, causing CGE to decline.

The consistently higher CGE values obtained with preheated air confirm that recovering waste heat from the syngas and using it to preheat the gasifying agent enhances the overall energy utilisation of the system. This improved utilisation means that a larger portion of the fuel’s chemical energy is delivered to downstream applications in the form of useful syngas, reinforcing the conclusion that heat exchanger integration is a beneficial strategy for small-scale biomass gasification.

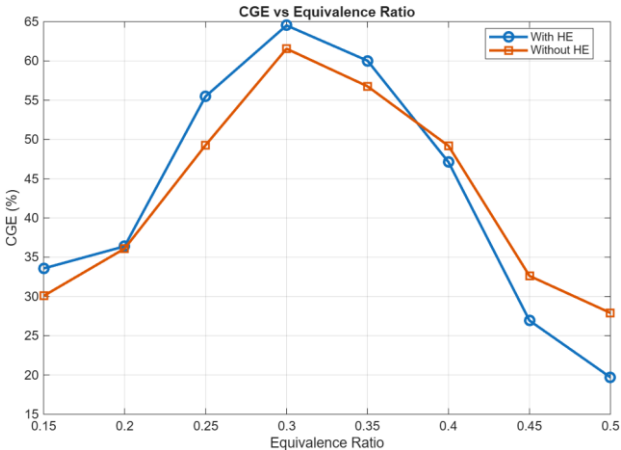


Figure 9: The cold gas efficiency of syngas

### 3.6 Overall heat transfer coefficient

The performance of the counter-flow heat exchanger integrated into the gasification system was evaluated by determining its overall heat transfer coefficient,  $U$ , under the different operating conditions. The overall heat transfer coefficient provides a measure of the combined effects of convection on both fluid sides and conduction through the separating wall, and thus reflects the effectiveness of the heat exchanger in transferring energy from the hot syngas to the incoming air.

The total heat transfer rate,  $Q$ , was calculated from the measured temperature changes and mass flow rates of the air and syngas streams using standard energy balance relationships. For a counter-flow heat exchanger, the logarithmic mean temperature difference (LMTD),  $\Delta T_{lm}$ , was obtained from the inlet and outlet temperatures of both fluids. The overall heat transfer coefficient was then evaluated using the expression

$$U = Q / A \Delta T_{lm} \dots\dots\dots (22)$$

where  $A$  is the effective heat transfer area of the exchanger. The relevant temperatures were obtained from the experimental measurements at steady state, while  $A$  was determined from the physical dimensions of

the heat exchanger tubes and shell.

The calculated values of  $U$  indicated that the heat exchanger provided a significant level of heat recovery, as evidenced by the increase in air temperature from approximately 28.3–29 °C at the inlet to 60.8–77 °C at the outlet. This rise in air temperature was achieved solely through the transfer of heat from the hot syngas stream, confirming that the exchanger operated efficiently within the tested range of syngas and air flow rates. The magnitude of  $U$  reflects the combined influence of flow regime, fluid properties, and the thermal resistance of the exchanger materials, and the obtained values are consistent with those typically reported for compact gas–gas heat exchangers used in similar applications.

The experimentally determined overall heat transfer coefficient thus provides quantitative evidence that the integrated heat exchanger is capable of recovering a substantial portion of the waste heat from the syngas. This recovered heat is effectively reused to preheat the gasifying agent, contributing directly to the observed improvements in syngas composition, lower heating value, and cold gas efficiency. As a result, the calculated  $U$  values not only characterise the thermal performance of the exchanger but also help to explain the enhanced overall energy performance of the downdraft gasification system when air preheating is employed.

The rate of heat transmission increased as a result. In a study by [31], the mass flow rate of water increased from 0.4 kg/sec to 0.7 kg/sec, showing a similar pattern of rise. When water was employed as both fluids, the heat exchanger's overall heat transfer coefficient rose from 129.2 W/m<sup>2</sup>K to 178.9 W/m<sup>2</sup>K.

According to [32], a parallel plate heat exchanger's overall heat transfer coefficient increased in proportion to an increase in fluid mass flow rate.

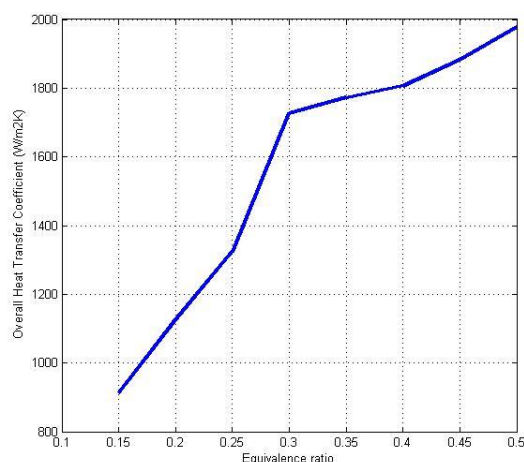


**Figure 10:** Variation of overall heat transfer coefficient

with equivalence ratio

### 3.7 Heat exchanger effectiveness

The effectiveness of the counter-flow heat exchanger was evaluated to quantify how closely the device approached ideal heat exchange performance under the experimental conditions. Heat exchanger effectiveness,  $\varepsilon$ , is defined as the ratio of the actual heat transferred to the maximum possible heat transfer that would occur if one of the fluids experienced the maximum feasible temperature change. For a gas–gas counter-flow heat exchanger, the effectiveness can be expressed as

$$\varepsilon = Q_{\text{actual}} / Q_{\text{max}} \dots\dots\dots (23)$$

where  $Q_{\text{actual}}$  is the measured heat transfer rate between the syngas and the air and  $Q_{\text{max}}$  is the maximum possible heat transfer based on the minimum heat capacity rate stream. The actual heat transfer rate was obtained from the product of the mass flow rate, specific heat, and temperature change of either the air or syngas, while  $Q_{\text{max}}$  was computed using the minimum heat capacity rate and the maximum potential temperature difference between the hot and cold streams.

The measured inlet and outlet temperatures showed that the air temperature increased from approximately 28.3–29 °C at the inlet to between 60.8 °C and 77 °C at the outlet, while the syngas temperature decreased correspondingly across the heat exchanger. These temperature changes, combined with the known flow rates and specific heats, yielded effectiveness values indicating that a substantial fraction of the available thermal energy in the syngas was successfully transferred to the incoming air. The effectiveness values obtained are consistent with typical performance ranges reported for compact counter-flow gas–gas heat exchangers and confirm that the unit was appropriately sized and operated for the intended application.

The high effectiveness of the heat exchanger explains the significant air preheating observed and supports the improvements in syngas composition, lower heating value, and cold gas efficiency documented in the preceding sections. By achieving a high degree of thermal utilisation of the hot syngas stream, the heat exchanger reduces waste heat losses and enhances the overall energy efficiency of the downdraft gasification system. This demonstrates that integrating an effective heat exchanger into small-scale biomass gasifiers can be a practical and impactful strategy for improving system performance without requiring additional external energy inputs.

As seen in Figure 3.7, the efficacy of the heat exchanger was assessed using variations in the equivalency ratio. It is evident that the effectiveness of the twin pipe heat exchanger is directly impacted by the equivalency ratio. As the equivalency ratio rises, so does the heat exchanger's efficiency. The effectiveness rises from 0.36 to 0.58 for equivalency ratios between 0.15 and 0.5. This is similar to the 0.50–0.58 effectiveness range noted by Simhadri et al. (2015) [33] for a twin pipe heat exchanger with and without twisted inserts.

According [34], the efficacy ranges of a twin pipe heat exchanger's plain tube, helical twisted wire tube, twisted clip, and threaded tubes were 0.29 to 0.36, 0.41 to 0.55, 0.44 to 0.48, and 0.32 to 0.43.

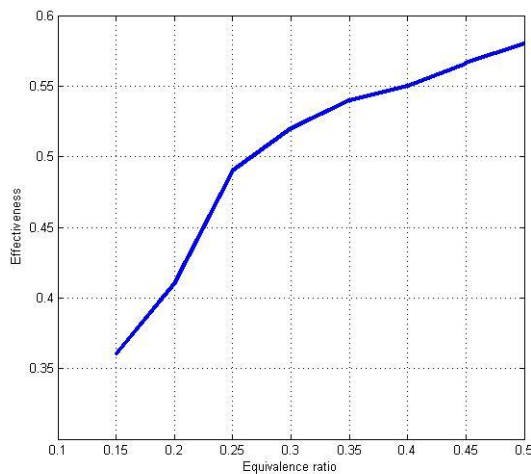


**Figure 11:** Variation of heat exchanger effectiveness with equivalence ratio

Another study by [34] indicated an optimal efficacy of 0.55, which was in good agreement with the current study's optimum effectiveness of 0.58. The subsequent work concentrated on generating turbulence in the inner and outer tubes to improve the heat transfer characteristics of a double pipe heat exchanger.

The trends in cold gas efficiency and heat-exchanger performance are consistent with recent regional analyses of environmental quality, urban climate and energy infrastructure in northern Nigeria, including studies on heavy-metal pollution indices, urban heat-island dynamics and the spatial distribution of petroleum filling stations [35 – 38].

The thermal-performance trends obtained in this work broadly agree with earlier studies on polymer heat exchangers and pulsating heat stripes [39;40]. Thermally conductive polymer composites can reach competitive effectiveness for water and energy recovery when channel

geometry is carefully optimised, despite their lower thermal conductivity than metals [39]. Detailed characterisation of polypropylene pulsating heat stripes shows that orientation, working fluid and loop geometry strongly influence heat-transfer rates, start-up behaviour and low-Reynolds-number penalties [40], while plastic heat stripes built from commercial materials can operate stably within defined pulsation regimes [41].

## IV. CONCLUSIONS AND RECOMMENDATIONS

This research focuses on the investigation of the effect of preheating the gasifying agent (Air) using a heat exchanger unit coupled to a downdraft gasifier outlet to extract heat from the produced syngas. The wood chips were prepared, characterized and used for the experiment varying equivalence ratio from 0.15 to 0.5. The syngas obtained at the various test conditions were characterized to ascertain the compositions of the combustible gasses present and determine the lower heating value and cold gas efficiency of the syngas.

### 4.1 Conclusion

Biomass gasification is one of the promising technologies for converting biomass into gaseous fuels. The high temperature producer gas obtained during gasification usually contains several contaminants such as tars, particules, etc. It is therefore necessary to cool the producer gas so as to easily clean it off tars and other contaminants.

The composition of combustible gases (CO, H<sub>2</sub>, and CH<sub>4</sub>) increased from ER of 0.15 to 0.3 (CO: 20.18% to 26.75%, H<sub>2</sub>: 5.67% to 13.39%, and CH<sub>4</sub>: 1.8% to 2.76% when using the heat exchanger and CO: 18.72% to 26.3%, H<sub>2</sub>: 7.77% to 16.24%, and CH<sub>4</sub>: 1.94% to 2.12% when not preheating the gasifying agent with an increase in ER of 0.5). A similar pattern was also seen in the lower heating value (LHV) and cold gas efficiency (CGE).

When a heat exchanger was used, the highest LHV and CGE were 5.1825 MJ/kg and 64.53%, respectively; in the absence of a heat exchanger, these values were 4.9435 MJ/kg and 61.56%. It is evident from the examination of the results that preheating the gasifying agent (air) produced syngas of higher grade.

### 4.2 Recommendation

The research's recommendations are as follows:

- a. Heat exchangers should be installed in downdraft gasifiers that use air as their gasifying agent in order to warm the gasifying agents.

Additionally, this lowers the temperature of the syngas that is created.

- b. To create the ideal operating conditions for the downdraft gasifier, more gasifying agents could be investigated.

**Author Contributions:** Concept, Design, Resources; Data Collection and Processing, Analysis and Interpretation, Literature Search, Writing Manuscript; Usiohen Iziegbe;

**Conflict of Interest:** The author has no conflicts of interest to declare.

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**Ethics Committee Approval:** The studies conducted within the scope of this article are not subject to Ethics Committee approval.

**Use of Artificial Intelligence:** Not Applicable

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