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ORIGINAL RESEARCH ARTICLE

# COMBUSTION MODELING OF A FIXED BED DOWNDRAFT BIOMASS GASIFIER USING COMPUTATIONAL FLUID DYNAMICS DESIGN

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**ABSTRACT**

Thermochemical conversion of biomass in a gasifier for the production of syngas provides the enabling technology for efficient biomass resource utilization. Gasification is a complex process involving the interactions of numerous parameters, hence CFD tool is usually utilized to numerically optimize the design and operation of the gasifier reactor for improved performance. The gasification of multiple biomass usually requires a complex set of facilities for experimental set up in order to determine the optimum operating conditions for maximum gas yield. When this is not available, it can pose a bottle-neck to process development and optimization. In this study, the GAMBIT and FLUENT were used to model and simulate the gasifier reactor with emphasis on the combustion and gasification (reduction) zones in order to maximize the thermal output of the combustor by an optimization of biomass fuel types. Model validation was achieved by showing a close agreement between numerical and experimental results within the same configuration, particularly to show the effect of temperature on the gasification of Fixed Bed Downdraft gasifier. The fraction of initial moisture content, air flow rate, temperature of the pyrolysis zone, and chemical composition of the biomass were the required input data for the model to predict the gasification temperature. Computations were carried out for rice husk, saw dust and corn cobs as gasifier fuels, whereby air was used as the oxidizing agent. The porosity and oxidizer velocity were varied between 0.1 – 0.5 and 5 – 15 m/s respectively. The predicted results compared with experimental data showed good agreement. The simulated temperature gradient also indicated that rich fuel combustion zone was greater for rice husk - corn cobs, an indication that improved gasification and pyrolysis were present.



## 1.0 Introduction

The utilization of biomass for energy is usually via the thermochemical conversion process from which the desired product may be gaseous, liquid and solid fuel respectively. Previous researches (Abdulrahman et al., 2016, Sharma and Sheth, 2016, Rahul Gupta et al., 2017, Zainal et al., 2001) aimed at the optimization of the gasification process have in addition to the experimental investigations conducted, also made significant efforts from numerical approach, whereby numerical models were developed using Computational Fluid Dynamics (CFD) codes such as ANSYS FLUENT and ANSYS CFX software. Simulation results from the numerical approach can help to optimize the system design and operation, in addition to understanding the dynamic process inside the reactor. Wang (2008) asserted that the entire thermochemical process has strong influence on the pyrolysis rate irrespective of the type of biomass or mechanism used. Recent modelling effort focused on the thermo-chemical equilibrium gasification model that described the application of one biomass fuel alone (Sharma and Sheth, 2016,), while attempt has also been made for the investigation of multiple fuels (Begum et al., 2013). Zainal et al. (2001) studied an equilibrium model based on equilibrium constants to simulate the gasification process in a downdraft gasifier and reported that the residence time of the reactants can be considered to be high enough to reach chemical equilibrium. Vaezi et al. (2008) conducted the simulation for the gasification analysis of 55 different biomass materials. The study which was aimed at the optimization of the biomass gasification operation produced a chart based on the predicted results that can be used to estimate the fuel characteristics value and ultimately the selection of a desired biomass material. Moreover, Mohan Raj and Srividhya (2013) conducted a performance analysis using a CFD simulation tool on a 20kW thermal gasifier plant which used wood chips as fuels, they varied the porosity at 0.525 – 0.439 and oxidizer velocity at 3 – 13m/s and found that there was more amount of unburned fuel at velocities 11m/s and 13m/s. they also reported that less amount of unburnt fuel and combustion stability were present at higher temperature when velocities was 4 m/s and 5 m/s. Muilenburg et al. (2011) investigated the CFD modeling of the combustion zone of downdraft gasifier by varying the bulk density, inlet velocity of oxidizer and fuel types. Furthermore, their report compared between wood chips and corn and observed that a fuel with packing density that correlate to porosity of 0.5 produced good results. Using both experimental and numerical method, Sharma and Sheth (2016) investigated the performance of a downdraft gasifier by varying the operating parameters such as moisture content, steam to biomass ratio and equivalent ratio via the equilibrium model approach to predict the composition of the producer gas and calorific value. Rahul and Gupta (2017) studied the performance analysis of a 10 KWE biomass downdraft Gasifier facility, in which a simple and economic technique was also developed to calculate the composition of the producer gas. The simulation was done through the specie transportation model with volumetric and particle surface reaction for the calculation of gas temperature and mass fractions.

However, the reviewed literatures did not indicate the effect of biomass mixtures on the corresponding gasification temperatures. The objectives of this study were to understand the effects of multiple fuel injections in the reduction zone of the gasifier on temperature profile. The mathematical model of the downdraft gasification was developed on the development of the gasifier combustion zone that used saw dust, rice husk and corn cobs as fuels by varying process parameters of oxidizer velocities and particle packed densities for the mentioned feedstock. This study applied CFD tool which numerically optimize the Fixed Bed (FB) Downdraft biomass gasifier developed by Abubakar (2013) for the gasification of rice husks.

## 2.0 CFD Methodology

### 2.1 Description of the Gasifier Model

Figure 1 shows the Downdraft Gasifier facility developed by Abubakar (2013) for the experimental investigation of the performance of biomass gasifier that used rice husk and saw dust as fuel. The gasifier facility is available at the Engineering Teaching workshop, University of



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Maiduguri. The dimension of the gasifier is shown in Table 1. This model was considered in this study.

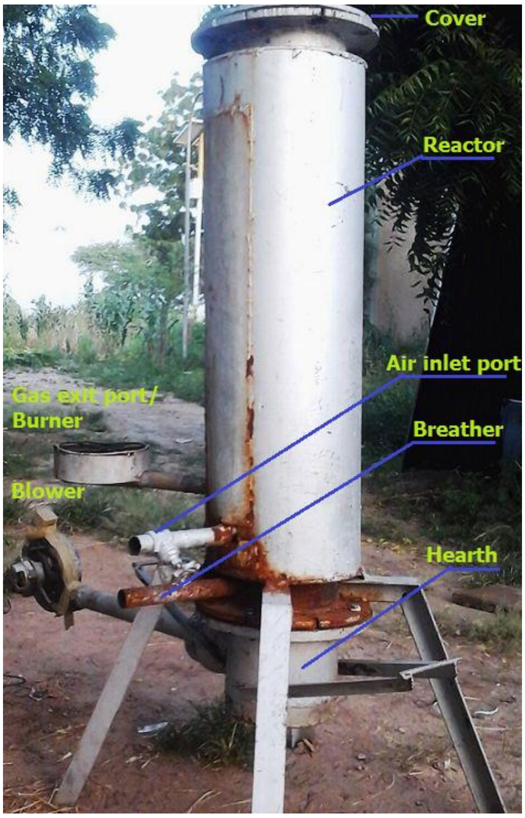


Figure 1: Downdraft Gasifier facility developed by Abubakar (2013)

Table 1: Dimension of the Gasifier

| S.N. | Parts of Gasifier | Dimensions (cm) |
|---|---|---|
| 1 | Outer shell diameter | 30 |
| 2 | Inner shell diameter | 20 |
| 3 | Height of gasifier | 101 |
| 4 | Thickness of shell | 10 |
| 5 | Insulation diameter | 30 |
| 6 | Air nozzle diameter | 3 |
| 7 | Length of air nozzle | 8 |
| 8 | Gas outlet diameter | 6 |

### 2.3 Model setup

A two-dimensional (2D) model of the FB Downdraft gasifier shown in Figure 2 was modeled using GAMBIT 2.2 and exported to FLUENT 6.2 solver for further analysis. The 2D representation of the gasifier reactor focuses on the combustion zone and was completed with meshes of 8000 elements.

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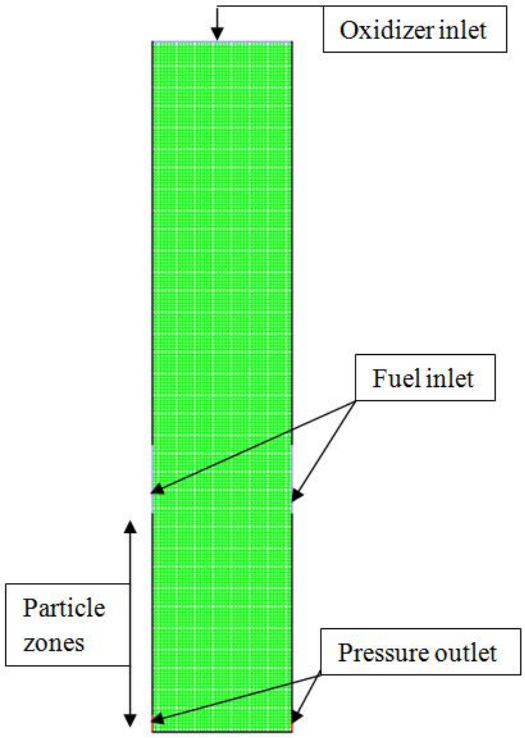


Figure 2: A 2-D Meshed Model of the gasifier.

## 2.4 Model Formulation

The equilibrium model (Sharma and Sheth, 2016) assumes that all reactions are in thermodynamic equilibrium, such that the residence time allow pyrolysis product to burns out completely and achieve equilibrium in the reduction zone. The general assumptions also include:

steady state flow i.e. zero dimensional

No-slip condition on wall surfaces, and the gasifier chamber is perfectly insulated

Dry air enters the chamber (relative humidity is zero), with 21% oxygen and 79% nitrogen by mass.

All carbon in solids are completely converted to syngas and all syngas exited the gasifier chamber

### *2.4.1 Governing Equations*

The process fundamental governing equations which describe CFD models for the thermochemical process of fluid flow, heat and mass transfer and chemical reactions are the conservation law of mass, momentum, and energy as presented in Equations (1) – (3) (El-jummah et al., 2015):

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x_i} \rho v_i = 0 \quad (1)$$

$$\frac{\partial}{\partial t} \rho v_i + \frac{\partial}{\partial x_i} \rho v_i v_j = - \frac{\partial \rho_i}{\partial x_i} + \frac{1}{Re} \frac{\partial}{\partial x_j} \tau_{ij} \quad (2)$$

$$\frac{\partial}{\partial t} \rho h + \frac{\partial}{\partial x_k} \rho h v_k = \frac{\partial}{\partial x_k} [\frac{\mu}{\sigma} \frac{\partial h}{\partial x_k} + \mu \sum_{\alpha=i}^{N} \left(\frac{1}{Sc_\alpha} - \frac{1}{\sigma}\right) h_0 \frac{\partial \gamma_\alpha}{\partial x_k}] \quad (3)$$

Where the following notations were used:

$\rho$, is density in kg/m3

v, is velocity of fluid flow across the control boundary in m/s

Re, is Reynolds number

h, is the enthalpy in KJ/Kg



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$\mu$, is the dynamic viscosity in Kg m-1 s-1

$\sigma$, is the Stefan–Boltzmann constant

And subscripts,

i, k, are the number of control volumes

j, is the reaction number

$\alpha$, N initial and final particle mass respectively

Selecting non-premixed combustion as the solver in FLUENT, while also applying the species transport phenomena, eddy dissipation and turbulent model as k-epsilon (Sharma and Sheth, 2016), the simulation was done for progressive change in the flow models by solving the conservation of mass, momentum and energy equations shown in Equations (1-3).

The chemical formula for biomass material takes the form $CH_xO_y$, whereby subscript x and y represents coefficients of the chemical species at molecular level of the biomass material. The global gasification reactions for biomass can be written as follows (Muilenburg et al., 2011):

$$CH_XO_YN_Z + wH_2O + SH_2O + m(O_2 + 3.76N_2) = x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76m\,N_2 \quad (4)$$

Where, the subscripts x, y, and z represents the number of atoms of hydrogen, oxygen, and nitrogen per one atom of carbon in the feedstock respectively, while w and m are the amounts of water and air, per one kmol of feedstock respectively. All inputs in Equation 4 are prescribed according to the operating conditions and the feedstock composition given by the proximate and ultimate analysis as shown in Table 2 and Table 3.

Table 2: Parameters for Boundary and Operating Conditions

| Boundary and Operating conditions | Specification |
|---|---|
| Air inlet temperature (K) | 300 |
| Fuel inlet temperature (K) | 300 |
| Equivalence ratio | 0.4 |
| Mass flow rate (kg/s) | 0.25 – 1 |
| Oxidizer velocity (m/s) | 0.1 – 0.5 |
| Moisture content (%) | 8.5 – 12.5 |
| Porosity | 0.1 – 0.5 |
| Gasifying agent | Air |
| Gasification pressure | 1 atm |

Table 3: Ultimate and Proximate Analysis for feedstock used for this study

| Fuel Types (Solid) | | Rice husk | Sawdust | Corn cobs |
|---|---|---|---|---|
| Ultimate Analysis | | | | |
| Carbon | wt % | 48.84 | 52.0 | 49.3 |
| Hydrogen | wt % | 7.24 | 6.07 | 5.7 |
| Oxygen | wt % | 42.84 | 41.5 | 44.6 |
| Nitrogen | wt % | 0.87 | 0. 28 | 0.4 |
| Sulphur | wt % | 0.18 | 0 | 0 |
| Proximate Analysis | | | | |
| Volatile matter | wt % | 68.8 | 80.7 | 77.8 |
| Fixed carbon | wt % | 13.5 | 8.6 | 15.6 |
| Ash | wt % | 10.1 | 2.7 | 0.8 |
| Moisture content (dry basis) | wt % | 7.6 | 7.8 | 5.8 |
| HHV (dry basis) | MJ/Kmol | 150.73 | 470.45 | 170.67 |

Source: Abdulrahman et al. (2016)

### *2.4.2 Boundary Types*

The boundary types as defined are oxidizer inlet, wall and pressure outlet. The air inlet was defined as velocity inlets, velocity inlet boundary conditions are used to define velocity and scalar properties of the flow at inlet boundary whereby mass flow rate, temperature of the mixture, mass fractions of all species in wood volatiles, turbulent intensity and hydraulic diameter are specified respectively. Table 2 gives the boundary conditions as used in the simulation process. Additional boundary conditions specified as well as material specification are shown in Table 4 and Table 5.

Table 4: Additional Boundary Types

| Zones Name | ID | Type |
|---|---|---|
| Fluid | 1 | Fluid |
| Centre | 2 | Symmetry |
| Outlet | 3 | pressure-outlet |
| Throat | 4 | Walls |
| Nozzle | 5 | velocity-inlet |
| Outer-wall | 6 | Wall |
| Fuel-hopper | 7 | Wall |
| Default-interior | 9 | Interior |



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Table 5: Material specification for fuel (solid) used; Rice husks, sawdust and corn cobs

| Property | Units | Methods | Values (s) |
|---|---|---|---|
| Density | Kg/m3 | Constant | 700 |
| Cp (specific heat) | J/kg-K | Constant | 2310 |
| Thermal conductivity | W/m-K | Constant | 0.17299999 |

While outlet surfaces were defined as pressure outlet boundary. When backflow occurs, specifications at the pressure outlet boundary becomes necessary and is suitable for both compressible and incompressible flows as was also observed by Vaezi et al., (2008). The outside surfaces were defined as wall boundary, no-slip condition was imposed on the surface giving that it is stationary, hence velocity is zero. For adiabatic case, the heat flux on the wall was also set to zero. Walls with constant temperature were assigned specified value. The reaction in the combustion zone of the gasifier determines the temperatures of the reactions in the other zones of the reactor.

### 2.5 Experimental Testing

In order to evaluate the performance of the gasifier, selected mixture ratios that are made up of rice husks and sawdust were batched fed and gasified using the test facility. The mixtures ratios were in accordance with the specification given by Abubakar (2013). Table 6 shows the test data comprising of the biomass mixture ratios weight of biomass (kg) used and time spent (s) for respective gasification experimentation and the corresponding gasification temperature.

Table 6: Measured Test Temperatures

| Ratio of biomass Feed | Qty of Feed (kg) | Gasification Temp (°C) | Time of stable flame (min) |
|---|---|---|---|
| 0:6 | 6 | 1100 | 15.5 |
| 6:0 | 6 | 768 | 27.3 |
| 6:1 | 7 | 800 | 35.3 |
| 6:2 | 8 | 810 | 36 |
| 6:3 | 9 | 880 | 46.5 |
| 6:4 | 10 | 890 | 63 |
| 6:5 | 11 | 950 | 95.7 |

Source: Abdulrahman et al. (2016)

Table 6 reveals that varying the quantity of feed in the gasifier across the mixed ratios, the maximum capacity of the gasifier was 11 kg. Feed left after gasification are within the range of 0 - 3.5 kg and feed consumed (burnt) which is also a fractions of the total quantities of feed used are within the range 5 - 8.2 kg. Time of stable flame in minutes was also reported for the entire experiment as between 15.5 – 95.7. The effect of feed mixture at 6:2 ratio shows that the quantity of feed consumed during gasification suddenly decreases when compared with the other test samples, it also records mild increase in the duration of gas flow when compared with 6:1 mixture. Considering that 6:1 mixture is the only case at which this mild change was observed, the addition of sawdust obviously has no further influence on the entire gasification test.

The gasification temperature ranges between 950 - 1100 °C for the entire gasifier tests, this is in agreement with the values from literature on the gasification temperature of rice husk and saw dust (Abubakar, 2013 and Begum, et al., 2013). This is satisfactorily, considering that the duration of gas flow is increased proportional to the quantity of fuel used and not the mixture ratio as found from the test (Abubakar, 2013).

## 2.6 Comparison of the Experimental and CFD Predicted Temperatures for Rice husk and Sawdust Gasification.

Figure 3 presents the relationship between measured temperatures reported by Abdulrahman et al. (2016) with the CFD prediction. The range of values for predicted gasification temperatures for rice husks and saw dust mixtures is 927 – 1125 °C. Maximum gasification temperature for the fuel mixtures is 1398 K (1125 °C) and this is close to the value measured experimentally, 1373 K (1100 °C) which confirms the adequacy of the CFD application.

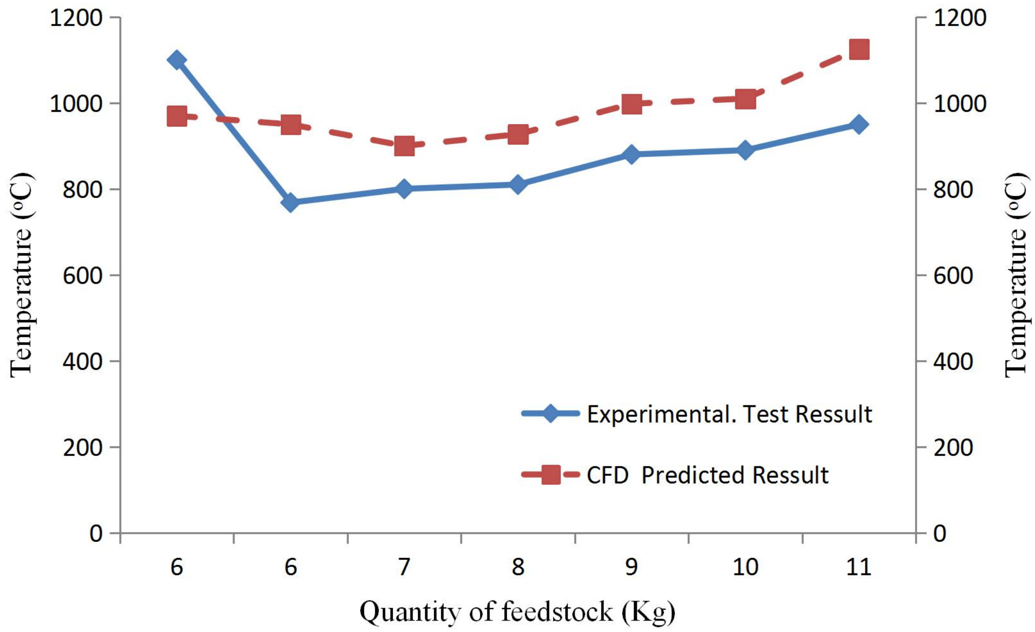


Figure 3: Experimental and Computational results for rice husk and sawdust

The relationship between experimental and predicted gasification temperatures was also evaluated by means of statistical approach as presented in Figure 4. The analysis indicate good agreement between the experimental and simulated results with $R^2$ value greater than 0.93.



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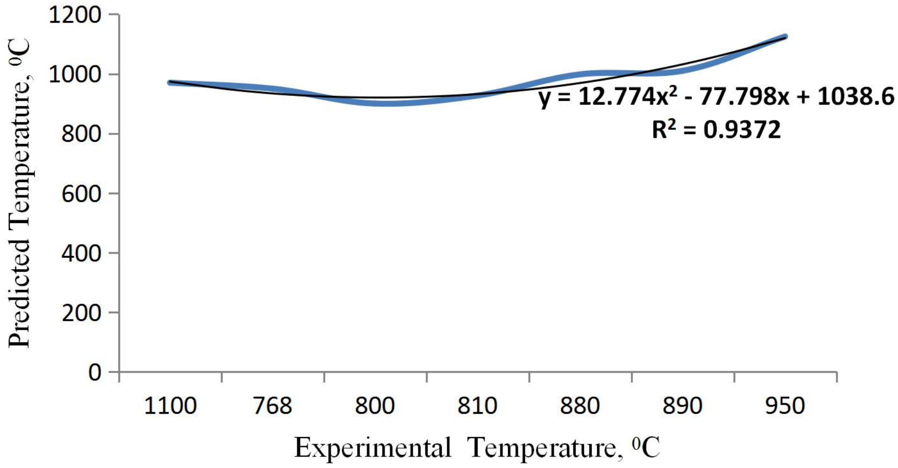



Figure 4: Experimental and CFD Predicted results validation

## 2.6 Model Validation

In order to validate the model, measured data reported by Abdulrahman et al., (2016) were used. Maintaining the same operating parameters as applied experimentally for the simulated results while also using rice husk and sawdust as feedstock, the predictions showed reasonable agreement which were statistically tested to have R2 value greater than 0.93 as shown in Figure 4. The comparison between numerical and experimental results are shown in Figure 5.

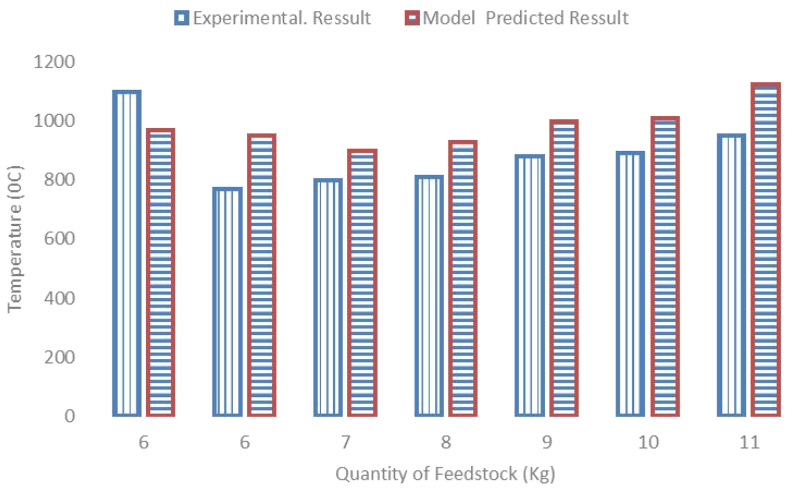



Figure 5: Graphical comparison between numerical and experimental results

From Figure 5, maximum reactor temperature reached for rice husk - sawdust mixtures after CFD analysis is 1398 K (1125 °C), this is close to the value measured experimentally (1100 °C). Furthermore, the range of values of predicted temperatures is 927 – 1125 °C. Considering that the predicted temperatures were higher than measured values is an indication that biomass fuel had adequate residence time in the reactor to actualize complete gasification as earlier observed by Muilenburg, et al. (2011). This indicates that computations of the other two fuels mixtures (i.e. rice husks - corn cobs and saw dust - corn cobs) could give reasonable and acceptable data that are expected to optimize gasifier design.

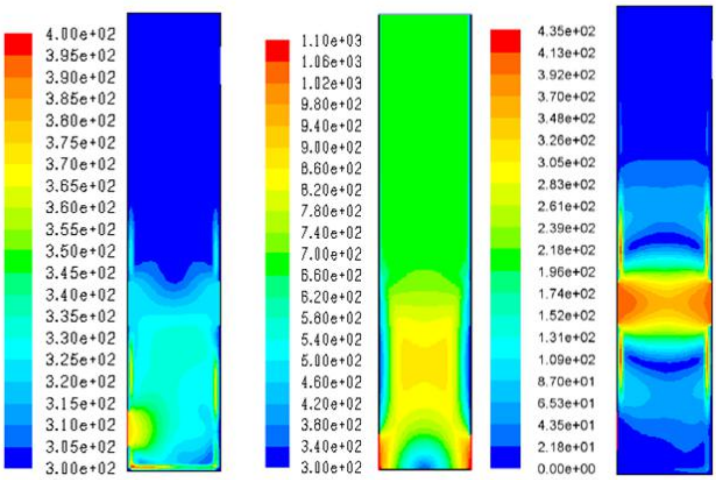
## 3.0 Results and Discussion

Figures 6 - 9 shows the contours of temperature gradients with variations in porosity, fuel types and velocity magnitude as well as the effects on fuel types are discussed as follows.

### 3.1 Influence of Porosity Variations on Temperature

The temperature gradient due to the variation in porosity for rice husk and sawdust mixture is shown in Figure 6. The first two contour plots (Figure 6a and 6b) of 0.1 and 0.25 porosities respectively shows that the gasification reaction is progressing. Considering that the reaction progresses from the combustion zone moving down to the lower part of the reactor for both plots, yet maximum temperature can be seen to be much higher (1100 K) in Figure 6b and relatively lower for 6a (400 K). Furthermore, Figure 6a appears to have an even control of temperature distribution at the region where temperature measured approximately 335 K. However, porosity of 0.25 has a more even distribution of temperatures throughout the porous zone as shown in 6(b).

At porosity of 0.5, maximum temperature of 1375 K was observed at the region where oxidizer and fuel combined as shown in Figure 6c this is an indication that biomass gasification of fuels (such as saw dust) with porosity of 0.5 has been fully achieved. Furthermore, temperature ranges between 1305- 1400k in this region. However, comparing Figure 6c with the first two cases shows that the majority of its post-mixture temperatures are greater than 700 K which indicates that a more even distribution of higher temperatures would be present since there appears an even mixture of fuel to oxidizer. The higher temperatures present also increases the chance for gasification and pyrolysis to occur in this zone and indicate that they would occur at a faster rate.



(a) Porosity 0.1 (b) Porosity 0.25 (c) Porosity 0.5

Figure 6: Contours of temperature gradient with variations in porosity

### 3.2 Influence of Fuel Types on Temperature

Biomass investigated also include mixture of rice husk and corn cobs, sawdust and corn cobs, which are all component of the study area. The porosity was kept at 0.25 and the oxidizer inlet velocity was set to 1.5 m/s while fuel mass flow rate was 1 kg/s. The ranges of temperature observed for the three fuel types indicated that: rice husk has 450 – 2300 K, sawdust, 350 – 800 K and corn cobs, 480 – 1100 K as shown in Figures 7a, b and c respectively. The temperature range for sawdust being the least low of the three fuels was attributed to the influence of moisture content of fuel material as was also reported for the experimental investigation of this study.



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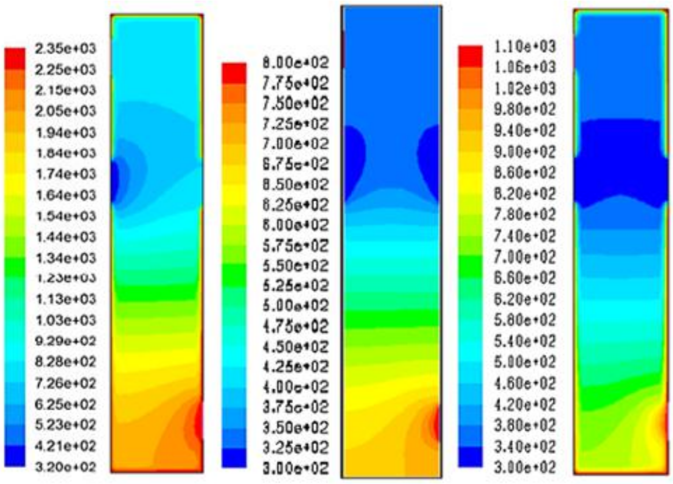
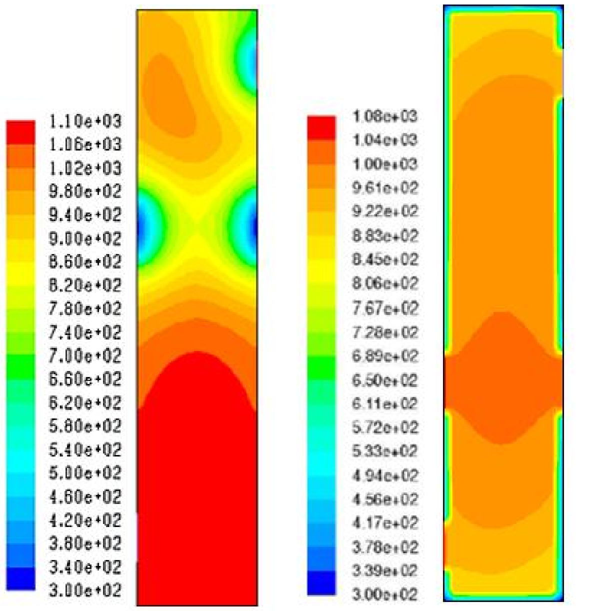
Figure 7c (corn cobs) shows a temperature gradient in which the central portion of the reactor refusing to light up, this may be attributed to corn cobs packing density which was mildly achieved at a porosity of 0.25 hence the air-fuel reaction and was progressing slowly. However, the hottest region can be found along the wall and towards the pressure outlet for both rice husk (930K) and corn cobs (1100K), although only a smaller region of the gasification zone of the reactor was covered in the case of corn cobs. The high temperature zone is always located in the vicinity of the fuel and oxygen blend. An improved temperature gradient of the reactor gasification zones was observed for rice husks (Figure 7a), which is in agreement with the result reported for the experimental investigation by Abdulrahman et al. (2016).




(a) Rice husk (b) Sawdust (c) Corn cobs

Figure 7: Contours of temperature with variations in fuel types

Figure 8 shows the variations in temperature with fuel mixtures. The mixture of rice husk – corn cobs as fuel produced temperature range of 300 – 1100 K (Figure 8a). While temperature range obtained for sawdust – corn cobs fuel mixtures is 300 - 1080 K as shown in Figure 8b. Usually, the porosity and moisture content of the fuels play a vital role in the distribution of heat in the reactor as observed in both cases. In addition, low temperature at the locality of exhaust gas outlet can be attributed to the reaction temperature distribution as observed in Figure 8a as compared with Figure 8b since in the latter it appears that hot wall impact is responsible for the internal conduction and chemical reaction of the reacting species, hence there is even temperature distribution in the reactor at the areas which serves as the oxidation and reduction zones where all the biomass fuel are burnt.




(a) Rice husk – corn cobs (b) Sawdust – corn cobs

Figure 8: Contours of temperature with variations in fuel mixtures

### 3.3 Influence of Oxidizer Velocity on Temperature

Figure 9 demonstrates that the oxidizer velocity makes a great deal of difference in the combustion of the biomass mixtures. At an oxidizer velocity of 1 m/s, the temperature gradient creates a bubble rising from the lower left corner up and to the right. Temperature ranges from 300 - 400 K as shown in Figure 9a and maximum temperature was observed near the right fuel inlet and moving against the left towards the pressure outlet. In Figure 9b, an oxidizer velocity of 5.0 m/s was set and it is observed that most of the fuel in the particle zone is burn off and the temperature gradient was also observed to have gradually risen up to the oxidizer inlet. The maximum temperature exists at the bottom wall and on the entire left side at 550 K while the arc of temperature around the combustion zone has a temperature of around 450 K.

At oxidizer velocity of 15 m/s, the temperature profile is much different as shown in Figure 9c. The gradient also increases quickly to the maximum temperature of 1100 K from 300 K which also stretches from oxidizer inlet along the left wall to the pressure outlet and considerable region of this temperature gradient lie between the ranges 300 – 1100 K. However, of all the three cases analyzed, case 2 with 5m/s oxidizer inlet velocity gave smaller area of unburned fuel within the combustion and gasification zones, this development was considered to be the best operating parameter since greater part of the gasifier combustor was covered and larger fraction of the fuel is burnt for maximum yield.



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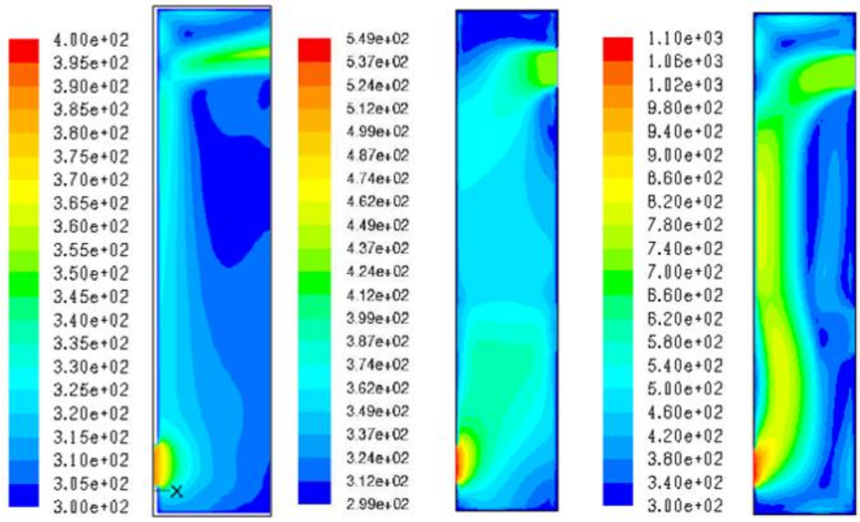


(a) 1 m/s (b) 5 m/s (c) 15 m/s

Figure 9: Contours of Temperature Gradients with variations in velocity magnitude

## 4.0 Conclusion

The study has successfully applied a CFD tool to numerically optimize Fixed Bed Downdraft Gasifier. The performance of the fixed bed downdraft gasifier in terms of the gasification temperature was obtained. It was observed that changing the porosity of the bed material in the particle packing zones (combustion and gasification zones) indicated that a fuel with a packing density that correlates to a porosity of 0.25 would be the best. This porosity produced an even temperature gradient to allow for a larger and more thorough combustion and gasification zone. The study further revealed that, at 5 m/s velocity inlet biomass material (especially rice husk and rice husk – corn cobs mixtures) gave smaller area of unburned fuel with smaller combustion and gasification zones.

The overall analysis of the three fuels computed showed that the corn cobs have large portions of the combustion and gasification zones and is within a temperature range of 300 – 1100 K, which is within the acceptable temperatures for gasification and pyrolysis to occur as earlier reported by Abdulrahman et al. (2016). Considering that both corn cobs and sawdust was used in this model, sawdust as biomass fuel appears to have a lower temperature gradient with a larger probability of gasification.

Using CFD as a design tool, mathematical and numerical methods were used to analyzed the gasification process of downdraft biomass gasifier with multiple fuels, the predicted results ensured the optimization of the biomass gasifier operating parameters with improved gasifier temperature.

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