International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

CFD Approach to Analysis of the Flow and Stoichiometric Properties in a Biomass Downdraft Gasifier Using Ansys.

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ABSTRACT

Biomass gasification is a promising thermochemical process for converting solid biomass into a combustible gas mixture, commonly referred to as syngas. This study employs Computational Fluid Dynamics (CFD) to analyze the flow behavior and stoichiometric properties in a downdraft gasifier using ANSYS Fluent. A mathematical model is developed to describe the four key stages of gasification: drying, pyrolysis, oxidation, and reduction. Governing differential equations for multiphase flow, mass transfer, and chemical reactions are numerically solved using an appropriate CFD approach. The results include solution contours for temperature, pressure, and species concentration, providing insights into the internal dynamics of the gasifier. The temperature distribution highlights the significant impact of airflow on combustion intensity, while the pressure contours indicate varying pressure zones across the gasifier stages. Species concentration analysis reveals the depletion of biomass and the formation of syngas components along the gasification process. The obtained CFD results are validated against existing analytical and semi-analytical models, demonstrating accuracy and computational efficiency. This numerical approach offers a robust tool for optimizing gasifier performance, particularly in scenarios involving complex geometries and boundary conditions.

Keywords: Computational Fluid Dynamics (CFD), Biomass Gasification, Downdraft Gasifier, ANSYS Fluent, Stoichiometric Properties, Temperature Contours, Pressure Distribution and Species Concentration.

Cite This Article As: Adebowale, P. A., Elegbede, K. T. &Igwebuike, K. U. (2025). CFD approach to analysis of the flow and stoichiometric properties in a biomass downdraft gasifier using ANSYS. International Journal of Research Publication and Review (IJRPR).

1.0 Introduction

1.1 Overview

The vociferous sound generated by the runners and stators of turbomachines, the hazards posed on remote organisms by the turbo plants, cost associated with production of solar energy, space consumed by solar panels, pollution issues associated with coal all call for a noiseless, cost effective and neat way of obtaining energy without producing much harm to the society. In view of the above mentioned constraints, researchers have worked fervently to discover that biomass is a better source of renewable energy compared to solar or wind energy. In fact, in some part of the world, the use of fossil fuels as a source of energy will soon become obsolete. In Nigeria for instance, petroleum is found to be on the high side in terms of cost, purity and availability.

The synthesis of energy via biomass is becoming of huge importance to this century. The technology of the biomass gasification process appears to gradually suffice as an auspicious substitute for other renewable sources of energy such as wind, solar, hydroelectric and tidal. The entire process is an endothermic thermochemical conversion of inputs (plant or animal biomass) into dominantly gaseous outputs (CO, H_2 and CH_4) having great heating or calorific values which can be easily maneuvered in most chemical industries. In addition, downdraft gasifiers have cleaner quality of producer gas compared to other gasifiers, this is due to their low tar content. The improved quality of producer gas therefore leads to high gasification efficiency hence gaining much global significance in today’s industries and markets due to the following reasons:

- ✓ It is a good waste disposal process.
- ✓ It is renewable
- ✓ It can be used in combined heat and power applications.
- ✓ It is environmentally friendly and clean
- ✓ It is cheap, cost effective as it reduces consumption of electricity in peak times.

- ✓ The products are gaseous and can therefore be directly used in internal combustion engines, producing fewer emissions.

1.2 Conceptual Review

Biomass: is fundamentally described as a form of renewable energy obtained from living or organic components in the society (plants and animals). The components from which the energy is derived are feedstock such as wood, coconut, cotton, palm nuts, sugar-cane, wheat, and sunflower, to mention a few. It is found as a source of fuel to machinery.

Gasification: is a specialized scientific process which involves the application of technological ideas to transform organic raw materials such as coal or biomass into fuel gas or syn gas (an acronym for synthesis gas). The whole process takes in a vessel known as gasifier at high temperature/pressure where limited oxygen and steam are directly mixed with coal or biomass leading to a sequence of systemized chemical processes that converts the raw material (feed) into syn gas and slag (residues).

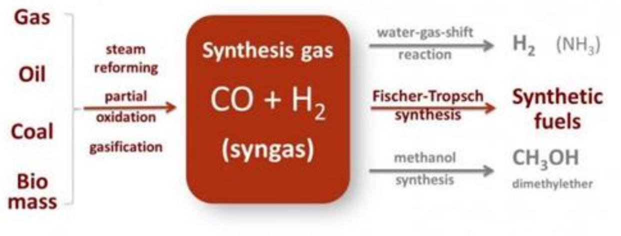
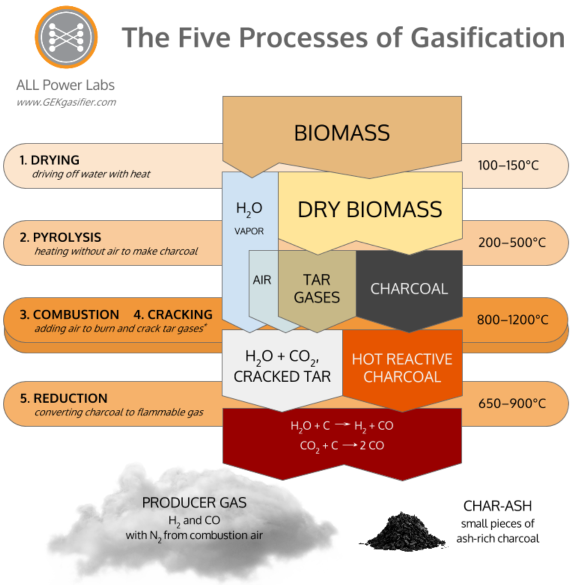


Figure 1.0. Schematic diagram showing how syn gas is produced

Source: syncat@beijing

The figure below depicts how gasification takes place, the sequential stages involved will be discussed in turns, the gases and incombustibles produced are also shown.



* tar cracking is the breakdown of tar into H_2, CO, and other flammable gases by exposure to high temperatures.

Figure 1.10: steps in gasification

Source: All flow lab.

a. **Drying:** This is a dehumidifying process which aids in the extraction of water away from the biomass and thereafter converting the water into steam.

b. **Pyrolysis:** This involves addition of heat to the dried biomass in limited supply of air or oxygen in order to split the biomass into charcoal and few traces of tar gases and liquid, a process otherwise known as charring. The decomposition of the biomass begins the moment its temperature raises beyond 514K, it disintegrates into solids (called charcoal), liquids and gases (called tar). The resulting gases produced contain a very high percentage of CO and H2, traces of hydrocarbons as well as unwanted nitrogen impurities.

c. **Combustion**: The gases produced when burnt in air undergoes combustion readily to give CO2 and H2O, only one oxygen atom is required to complete the combustion, the combustion is thus a single step and a very clean process.

d. **Cracking:** This involves thermal decomposition of the giant tar molecules obtained from the pyrolysis stage. This takes place at a temperature range between 800-1200°C in the gasifier. The resulting gases produced aftermath of cracking is clean and can be used directly in internal combustion engines without fouling.

e. **Reduction**: This is a direct reverse of combustion; it simply involves the removal of oxygen atom from the products of combustion in order that they may burn again. The process takes place at elevated temperatures.

Types of Gasifier

Previous researches showed that there are several types of biomass gasifiers some of which will be highlighted and discussed below:

ACCORDING TO THE DIRECTION OF AIR OR GAS FLOW AT EXIT

a. **Downdraught gasifiers:** They are otherwise known as concurrent gasifiers. The basic gasification air is supplied either at the oxidation (combustion) region or above it. Producer gas is thus removed at the lower part of the setup, being co-current means fuel and gas move in the same direction. One very good advantage of this gasification technique is that it offers solution to tar entrainment in the gas streams. Meanwhile, this type of gasification has some setbacks among which are inability to operate on a number of unprocessed fuels, higher ash or slag content compared to updraft gasifiers, lower efficiency due to minimal heat exchange and lower calorific value of the gas.

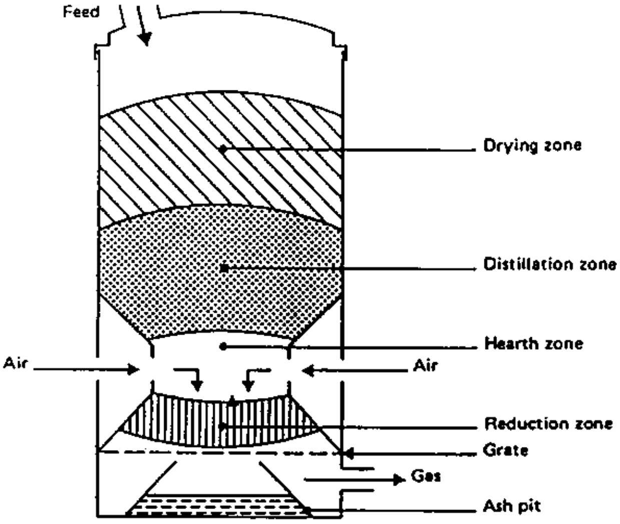


Figure 1.2: A typical downdraught gasifier.

Source: www.fao.org

b. **Updraft (counter-current) gasifiers**: In these types of gasifiers, air is supplied at the bottom and the gas leaves at the top. At the top, heating and pyrolysis of the feedstock occur through forced convection and radiation from the downward regions. The tars and other volatiles produced during the process will be carried along with the gas streams, ashes or slags will escape via the lower part. This process is alternatively known as counter current gasification, it is the earliest and easiest form of gasification ever known, highly efficient and can operate with wide varieties of feedstock (sawdust, rice, etc). However, this method of gasification is found to be faced with tar entrainment challenges.

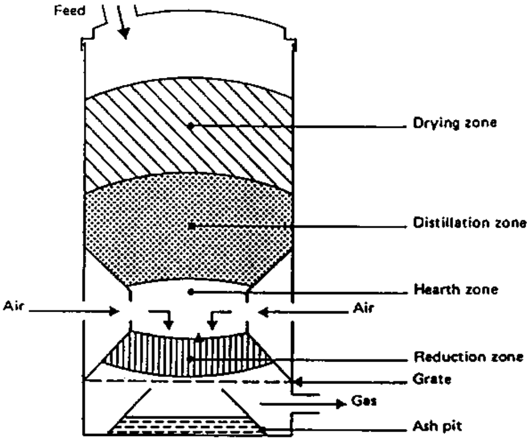


Figure 1.3: Updraught gasifier

Source: www.fao.org.

c**. Cross draft gasifiers:** Fuel or feedstock is supplied from the apex of the set up and gas is ejected via a nozzle from one side. It is suitable purposefully for the use of charcoal and there is a net high temperature in the oxidation zone (temperature at oxidation zone is estimated to be minimum of 1773K). One interesting feature about this type of gasifier is that the fuel (charcoal) provides self-insulation. It bears an analogy with the counter-current gasifier in the sense that the fuel (feedstock/charcoal) enters from the top but the air (gas) enters from the side rather than from the bottom or top.

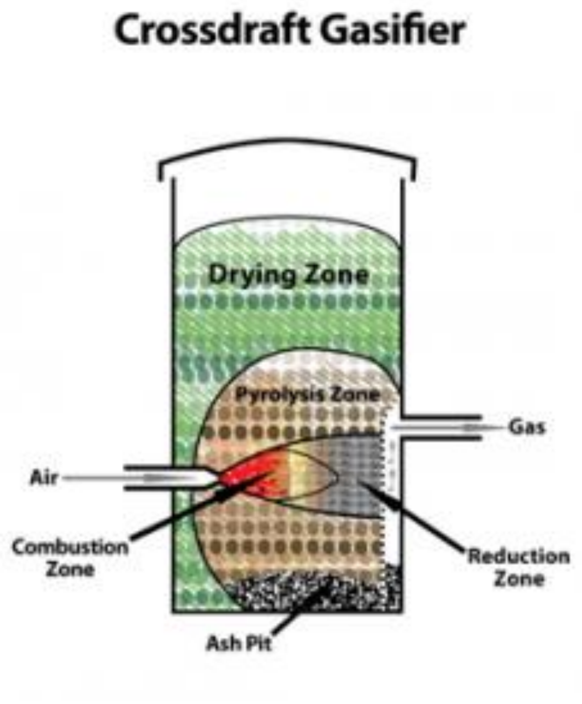


Figure 1.4: cross-draught gasifier.

Source: www.fao.org

ACCORDING TO THE NATURE OF THE BED

There are two types of gasifier in this class, they are:

- **Fixed gasifiers**:The types of gasifiers discussed above are typical fixed bed gasifiers. Such gasifiers contain a fixed bed of biomass which conveys the oxidation medium updraft or downdraft.

b. **Fluidized bed gasifiers**: This is a combined operation of both up and downdraught gasification process which is influenced by improving the properties of the fuel. Air is first supplied to a packet(bed) of solid particles which is externally heated, the feedstock (biomass) is then introduced upon attaining a sufficiently high temperature, the fuel particles are quickly introduced in order that they may attain thermal equilibrium with the bed surface. The pyrolysis is very fast, resulting in great number of gaseous materials.

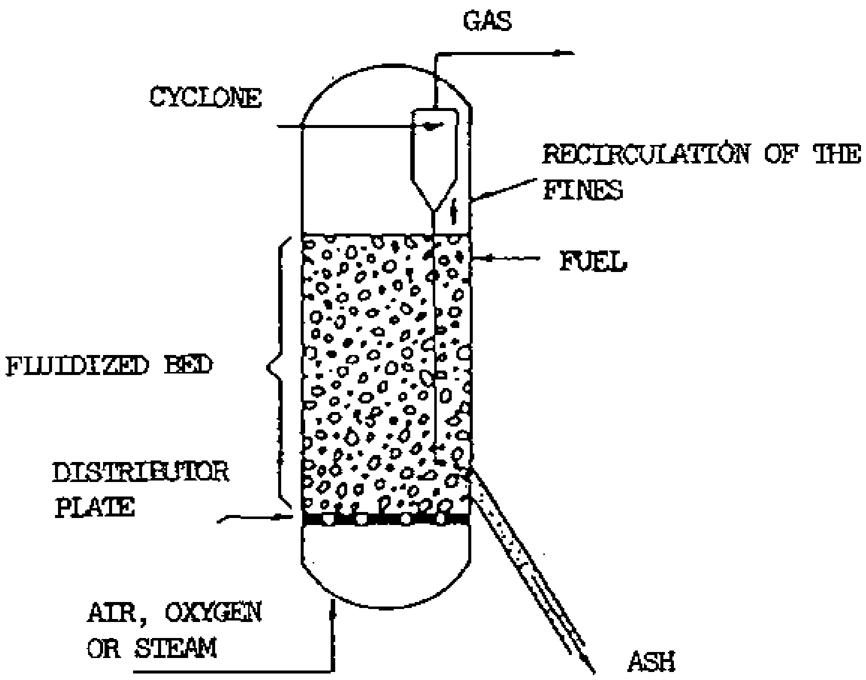


Figure 1.5: Fluidized bed gasifier.

Source: www.fao.org

1.3. Aim and Objectives

The aim of this research is to carry out a numerical analysis of the processes in gasification. To achieve the aim, the following objectives will be put into consideration:

1. Mathematical equations in form of differential equations will be illustrated for the gasification stages.
2. The differential equations will be solved for each stage with the aid a appropriate method of analysis, using ANSYS Fluent.
3. Upon solving the equations, the solution contours are obtained and discussed appropriately.

1.4 Scope

The differential equations for modeling the multiphase flow through the gasifier are all available in literature. The approach to solving the equations in this work will be numerical.

2.0 Literature Review

The history of gasification can be traced back to the late early 18th century. The process was initially used to produce town gas for lightning and cooking with electricity and natural gas eventually replacing town gas. However, Jean Baptista, a famous Belgian chemist and physician in 1609 already found that gas could be produced as a product when wood or coal is subjected to sufficient heating. Lawrence et al (2021) stated in their work that over eleven (11) main gasifiers are being distributed for marketing as at 2021 with several other forms of gasifier available for converting raw feedstock (biomass) into syngas of great quality, they reviewed the hydrodynamics and kinetics of each gasifier type stating distinctions between their performance. Dutta et al (2014) built a stoichiometric model for a downdraft gasifier based on equilibrium constants. The outputs of their modeling were fairly good and agree quite well with experimental results for five different feedstocks. In addition, Ebubekir et al (2017) also carry out similar research to Dutta et al. They developed a semi-empirical equilibrium model for downdraft gasification system to predict the chemical composition of the syngas and the yield of tar for different equivalent ratios.

Hafiz et al (2020) quoted that '**biomass gasification is the most reliable thermochemical conversion technology for transforming biomass into such gaseous fuel as H_2, CO and CH_4'.** In order to obtain a better and accurate result, Carvalho et al developed a new method which involves rectification or modification of equilibrium constants two stages. In the first stage, an equilibrium model M1 is developed and tested against experimental data for significance, the M1 model was then modified in the second stage to a new model M2 which is termed a quasi-equibrium model. The effect of air/fuel ratio and moisture content on producer gas composition was predicted by a mathematical model developed by Perez et al.

One of the contemporary works on kinetic modeling was carried out by Budhathoki (2020) who considered a model of combining kinetic and thermodynamic equilibrium approach. He merged the kinetic reduction for reduction zone with the thermodynamic reduction for other zones. His finding was juxtaposed with existing experimental works on wood biomass and was found to be consistent for the gas composition less for methane in which it gave a higher production rate. The model further introduced a sensitivity analysis to study the effect of changing equivalent ratio and moisture content. More recently, an experimental and kinetic modeling study on how methanol is synthesized from hydrogenation of carbon dioxide (CO_2) using indium oxide as catalyst was performed by Screetama et al (2021). In their research, CO_2 is catalytically converted into improved chemicals and useful fuels by using high energy hydrogen derived from biomass reforming. The methanol being produced serves as a fuel with high calorific value. The two most considered reactions in their work are the methanol synthesis process (popularly referred to as the Reverse Water-Gas Shift reaction) and the well renowned Sabatier's reaction (hydrogen synthesis process). Xuantian et al (2004) also performed biomass gasification study in a circular fluidized bed. The effect of moisture content and A/F ratio on four zones modeling of a biomass downdraft gasifier was being investigated by Dejtrakulwong and Patumsawa (2014). Another interesting work on biomass gasification can be found in Orisaleye and Ojolo (2010) Journal of Energy and Power Engineering. They devised and developed a laboratory scale biomass gasifier which delivered a mechanical and thermal power of roughly 4kW and 15kW respectively. The gasifier contained a water seal and cover, it was being tested in two modes; **natural** and **forced downdraft modes**. The feedstocks (biomass) used were wood shavings and palm kernel shells. In the natural downdraft mode, the gasifier did not produced syngas whereas in the forced downdraft mode, a gas was produced which burnt to produce a luminous flame 15minutes per kg of biomass fed. The forced downdraft mode was thus found to have a better thermal performance. Jayah et al (2003) earlier performed computer simulation of a wood gasifier for tea drying. The computer program contained two sub-models (**pyrolysis** and **gasification**). The pyrolysis sub-model was used in determining the highest possible temperature and the chemical composition of the gases gaining entrance into the gasification zone while the gasification sub-model was caliberated and scaled with the aid of previously existing experimental data and information. They deduced that gasification zone should be made to last longer to achieve an acceptable conversion efficiency. Their findings further dictate that wood gasifiers appear to be a feasible way of producing the hot air for drying tea in Sri Lanka.

The analysis performed in this work bears much similarity with the research earlier carried out by Kumar et al (2008). They formulated mathematical models which characterize the gasification performance of a typical biomass gasifier, the mathematical models were solved analytically while a computer programme constructed in c language was used in obtaining the characteristic profiles along the reactor axis. The profiles obtained include those of temperature, concentration, efficiency and distance of particle travelled. They further studied and discussed the effect of moisture content, wood diameter, throat angle, throat diameter and preheated air on each of the profiles.

Recently, Zhang et al. (2024) in their work on Numerical Simulation and Analysis of Biomass Gasification and H_2-rich Production gave a more detailed evaluation of how the gasification system performs under several operating conditions for producing excess hydrogen gas. Janajreh and Shrah (2013) previously employed numerical and experimental approach to investigate downdraft gasification. They employed wood-chips as biomass feedstock and used the k-ε model in a CFD process of high resolution mesh.

In this research, the chemical kinetics model will be employed in analyzing the gasification process. The equations obtained will be solved on ANSYS Fluent solver coupled with the stated assumptions and boundary conditions all given in the next chapter. This research is not limited to only one type of feedstock (wood), similar to the feedstock employed by Enget (2020).

3.0 Methodology

Mathematical Modeling:

Mathematical modeling is a mechanism which applies precursory knowledge of the nature of the system being modeled to foretell how it will behave under a particular condition. In some cases, modeling makes it possible to have a better understanding of the behavior of a system that may on the contrary be difficult to ascertain experimentally. Also, mathematical models describing a process give room for some level of flexibility in the event of any alteration in the parameters of the biomass (feedstock) used or the conditions of equipment utilized in the process.

Generally, in the modeling endemic to biomass gasification it is essential to note that the process takes place in four steps: **drying, pyrolysis, oxidation and reduction** as discussed earlier. The mathematical model is thus developed for each stage in the process.

There are three major ways in which gasifiers are modeled numerically or computationally, each method aims at simulating the behavior and performance of the gasifiers. The methods are: **thermodynamic (chemical)equilibrium models, kinetic models** and **Computational Fluid Dynamics (CFD)**. A brief discussion of each model will be given below.

4. Thermodynamic Equilibrium Model (TEM)

This modeling method offers a rational speculation of syngas production and greatest possible temperature attained in the chemical reaction. It relies on chemical balance and is hinged on combining the equilibrium constants (called stoichiometric approach) with the optimization Gibb's free energy and entropy (nonstoichiometric approach) through a single global or multiple chemical reactions. However, it usually performs over prediction for some species like CO and CH_4 and it cannot be applied in the prediction of such other parameters as gasifier design, velocity and temperature distributions.

The optimization process in TEM is popularly referred to as the nonstoichiometric approach, it basically involves the maximization of entropy and thus minimization of Gibb's free energy of a reaction. In this approach, only the ultimate analysis of the feedstock is required as input to be processed, it is thus categorically suitable when the actual chemical formula or possible chemical reactions of the feedstock or the process is unknown, as found in gasification.

Mathematically, Gibb's free energy is given by:

$$G = \sum_{i=1}^{N} n_i \mu_i$$

Where:

n_i = number of moles of species i

μ_i= chemical potential of species i.

Also, $\mu_i = G_i^\theta + RT \ln \frac{f_i}{f_i^\theta}$ 2

Where:

G_i^θ denotes gibb's free energy at standard conditions

f_i is the fugacity of species i (partial pressure of the specie in the non-ideal state)

In addition, if fugacity coefficient, ψ is invoked, E. 2 becomes:

$$\mu_i = G_i^\theta + RT \ln \frac{\psi P_i}{P_i^\theta} \tag{3}$$

Meanwhile, for an ideal gas at atmospheric pressure, we have:

$$\mu_i = G_{f,i}^\theta + RT \ln y_i \tag{4}$$

$y_i =$ mole fraction of species i, can be express as:

$$y_i = \frac{n_i}{\sum_{i=1}^{N} n_i} \tag{5}$$

For a pure element, the standard gibb's free energy of formation of species I will be zero. Thus, the net Gibb's free energy of a system is:

$$G = \sum_{i=1}^{N} n_i (\Delta G_{f,i}^\theta + RT \ln \frac{n_i}{\sum_{i=1}^{N} n_i}) \tag{6}$$

Lagrange multiplier can then be used to minimize G and obtain the corresponding n_i which optimizes the objective function. Applying molar balance of atoms, we have:

$$A_j = \sum_{i=1}^{N} a_{ij} n_i , \quad j = 1, 2,3, \dots , k. \tag{7}$$

$$L = G - \sum_{j=1}^{k} \lambda_j \left(\sum_{i=1}^{N} a_{ij} n_i - A_j \right) \tag{8}$$

Finally, the partial derivatives with respect to n_i are set equal to zero in order to obtain the minimum point:

$$\frac{\partial L}{\partial n_i} = 0 \tag{9}$$

A set of N nonlinear algebraic equations coupled with k atomic balances help determining the N values of n_i equilibrium using k Lagrange multipliers λ_j. The resulting algebraic equations can then be solved using an iterative technique (such as Newton-Raphson method).

5. Kinetic Modeling

Kinetic models are popularly used as they span through diverse range of parameters that cannot be scrutinized by thermodynamic equilibrium models. It gives detailed information about the chemical reactions taking place inside the gasifier. It is also found to be efficient for speculation of gasifier design, fuel feeding rate, residence time, and reactor hydrodynamics. However, kinetic model is known to have some limitations in gasification process. The interactions between solid and gas phase reactions during gasification process needs clear understanding and cannot be covered during kinetic modeling. Kinetic models are capable of predicting the overall system performance, including the output of producer or syn gas and the temperature profiles as well as producer gas composition along the gasifier. They are more accurate and elaborate compared to thermodynamic equilibrium models, but are also intricate, containing a number of characteristic parameters that usually limit their applicability.

Computational Fluid Dynamics (CFD) Approach

This is an exceptional and efficient numerical modus operandi which gives room for a scrupulous scrutiny of all the processes endemic to gasification. It proffers a quite better way of visualizing and hence understanding multiphase reactions (such as solid-gas phase reactions) during gasification process. A complete CFD model incorporates all equations and parameters related to mass transfer, momentum transfer, energy conservation, turbulence as well as hydrodynamics of fluid flows. There are diverse varieties of CFD modeling and simulation packages universally available such as Star CCM, Autodesk CFD, ANSYS Fluent, ANSYS Forte, CONVERGE, Elmer, COMSOL Multiphysics, XFlow, IVRESS, FlowVision and lots more.

However, the shortcoming of CFD modeling is in the area of biomass gasification due to biomass variety and also inadequate understanding of tar formation models.

Among the three methods mentioned above, the CFD approach will be employed, the method is chosen to solve the appropriate mathematical models faster with greater accuracy and convergence. In addition, the method affords researchers or learners to have a better view of the model or system under investigation. The method begins by first obtaining a draft of the gasifier’s geometry on SOLIDWORKs Design Modeller as shown in the figure below. The model is then imported to ANSYS Fluent which creates a mesh of the model based on Finite Element Analysis in order to discretize and solve the governing differential equations. The model diagram along will all the flow parameters evoked are stated below.

Geometry of Gasifier: The biomass downdraft gasifier is model using solidworks which is made with aluminum

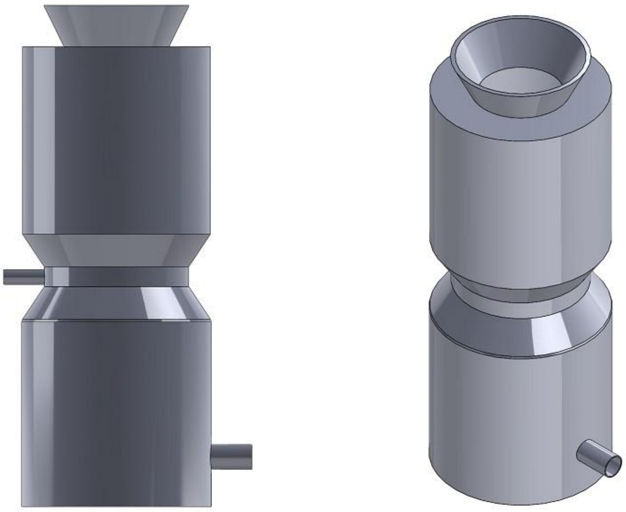


Figure 3.0: Gasifier’s Geometry drafted on SOLIDWORKs

The mesh is created using a total number of 120463 nodes and 538574 element.

Parameters employed

Biomass diameter (150µm)

Thermal conductivity k = 0.689W/mK ; Cp = 1800J/kgK ; Density, $\rho = 800$kgm^{-3}.

Air inlet conditions: Mass flow rate (0.205kg/m^3), O_2 = 0.23; Temperature of air = 168^{o}C (441K)

Biomass inlet conditions: mass flow rate (0.0025), biomass volume= 1.00m^3, Temperature = 127^{o}C (400K)

Outlet syngas: pressure = 40kPa, CO_2 = 0.169, Temperature = 1000K

All the above listed parameters of air biomass and syngas are evoked at inlet of the gasifier and the ANSYS Solver, equipped with necessary equations for carrying out the mathematical analysis helps solve the conditions of air and biomass in the gasifier up to the exit level. The results are presented and discussed subsequently.

4.0 Results and Discussions

Temperature contours: It is observed from the temperature distribution that the air flow inlet has a significant impact on the temperature of the gasifier leading to increase temperature in the focus point of the air. This indicate intense combustion and heat generation.

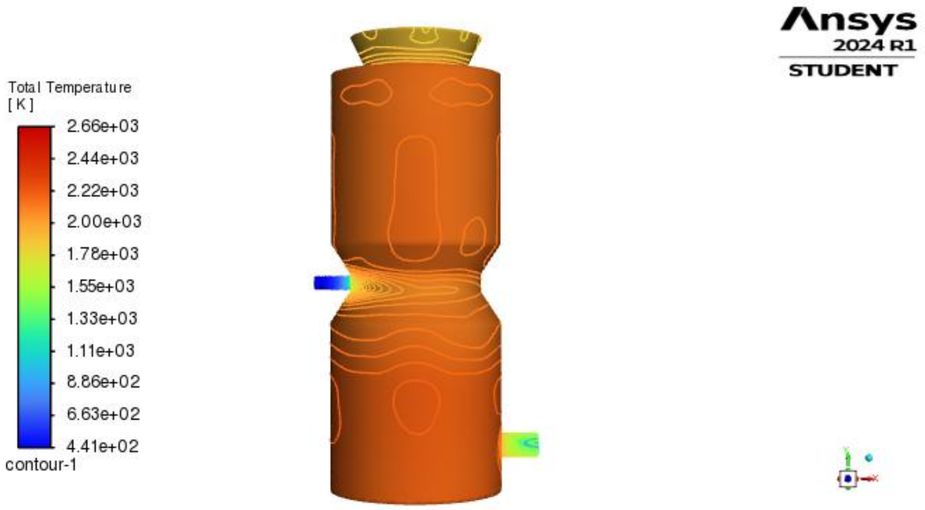


Figure 3.1: Temperature Contour

Pressure contours: The pressure distribution in the downdraft gasifier indicates the pressure at each zone of the gasifier, which are as follows **feeding zone** (lowest pressure), **drying and pyrolysis zone** (having the highest pressure), **oxidation zone** (low pressure). However, due to the effect of pressure in the **pyrolysis zone**i.e pressure first increases in the specific area initially rise and then it decreases, the reduction zone/syngas (high pressure).

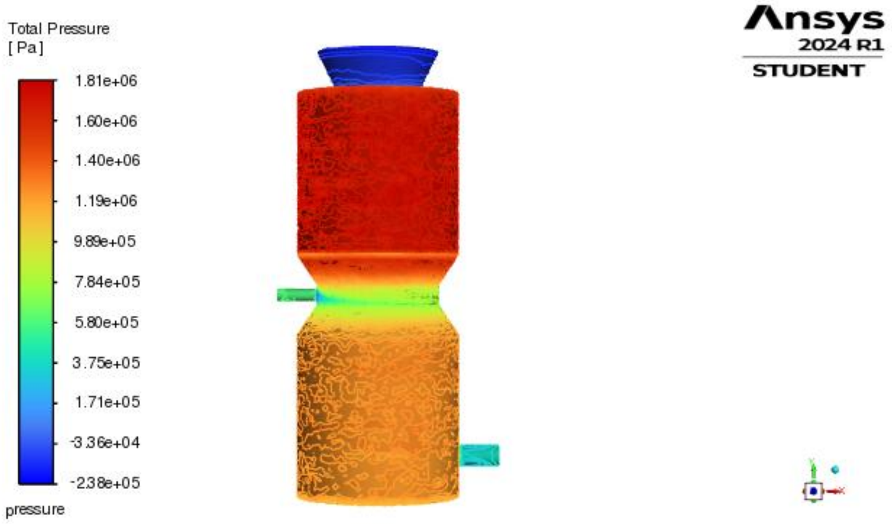


Figure 3.2: Pressure Distribution at each zone of the Gasifier

Species concentration contours

1. For the biomass(wood), **the mole, molar** and **mass fraction** are shown respectively. It is observed that the molar concentration of the wood (Biomass) is high at the feeding zone and it decreases significantly down the gasifier. This being caused by the reactions undergone by the biomass at each zone of the gasifier.

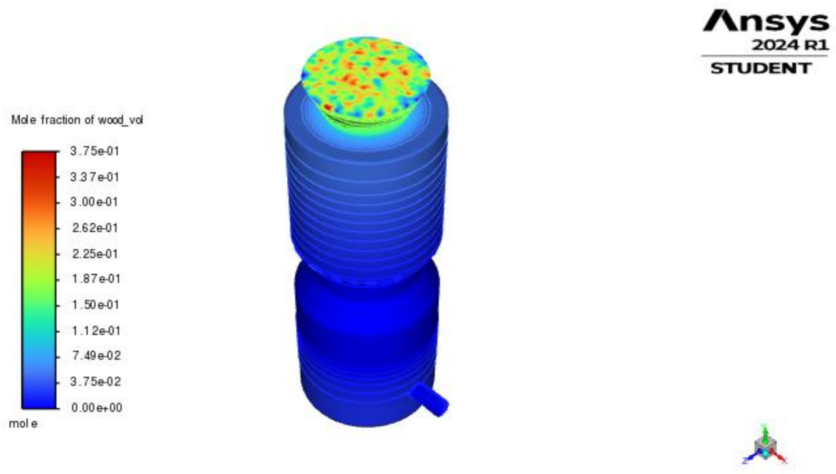


Fig 3.3a: Mole fraction of Wood

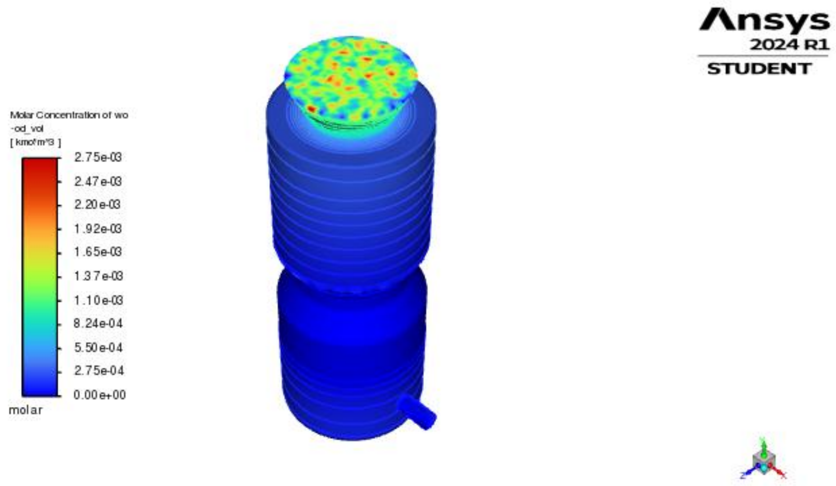


Figure 3.3b: Mass concentration of wood

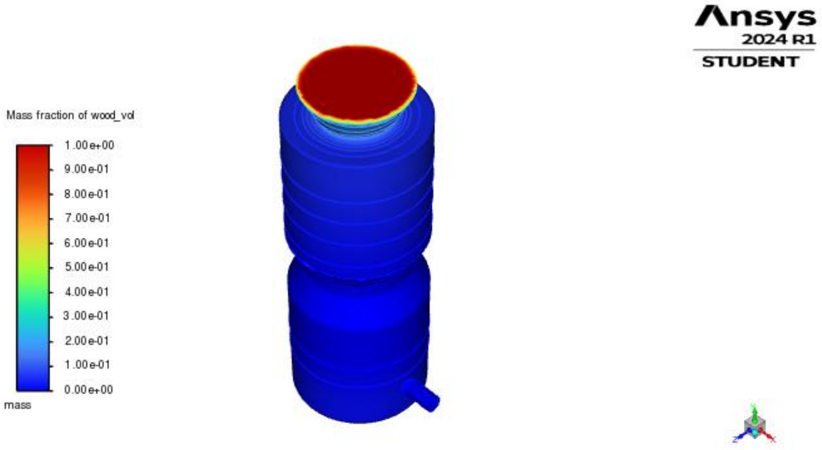


Figure 3.3c: Mass fraction of wood

2. The distribution of the mass, mole and molar fractions of oxygen are shown respectively. It is observed that the concentration at the air, though initially concentrated at entry to the gasifier, later distributes evenly in the entire gasifier. Oxygen therefore plays a crucial role in the oxidation zone.

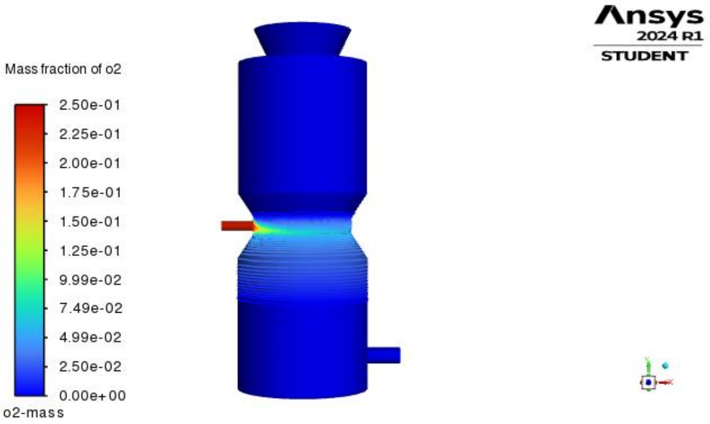


Figure 3.4a: Oxygen mass fraction

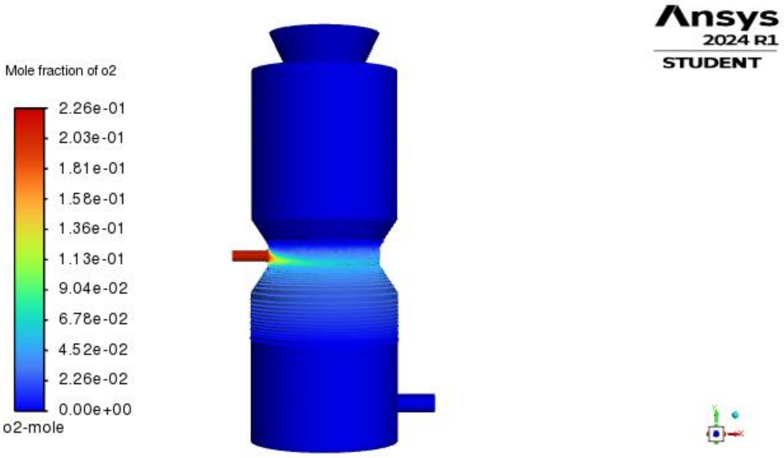


Figure 3.4b: Oxygen mole fraction

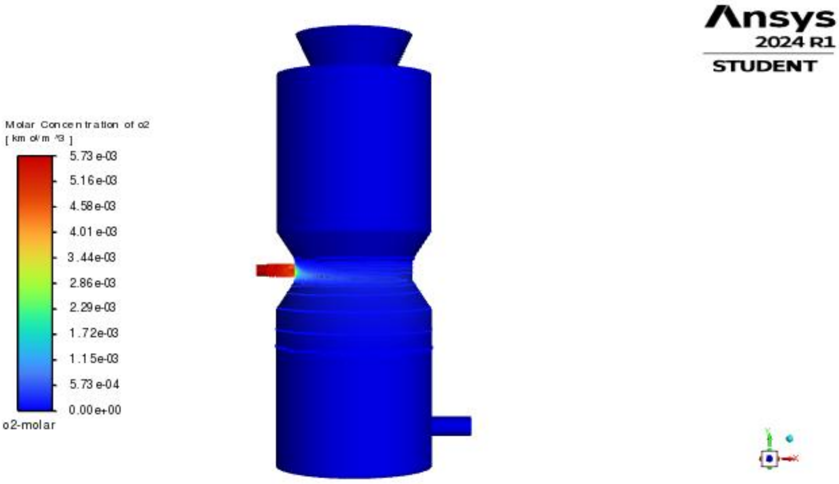
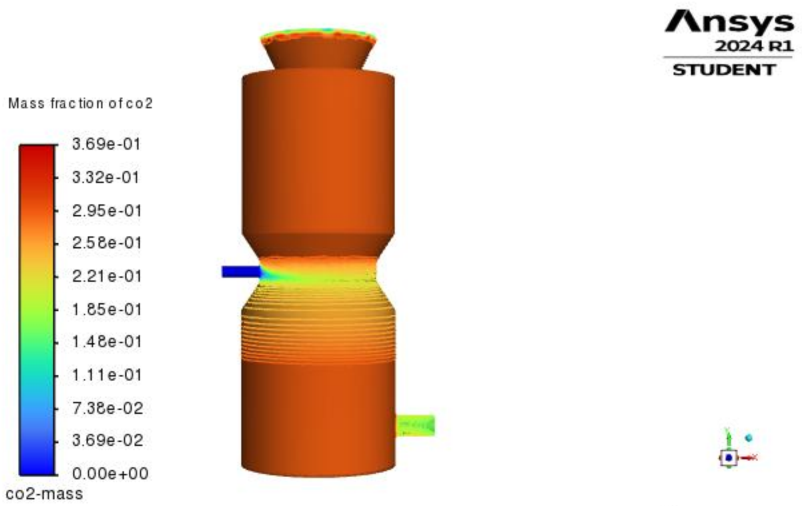
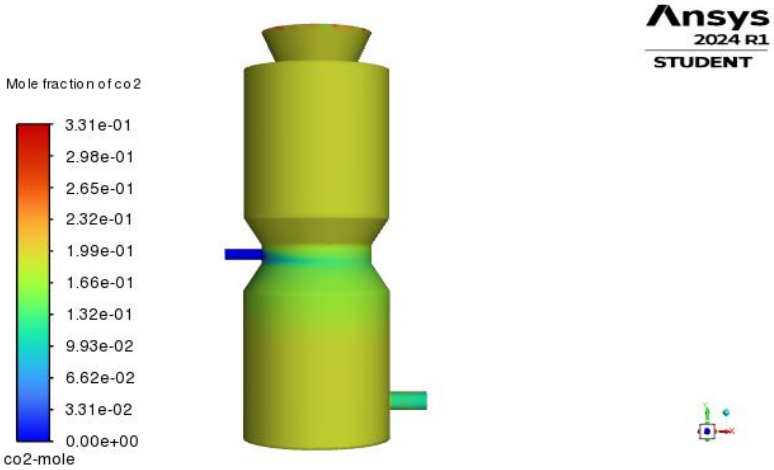
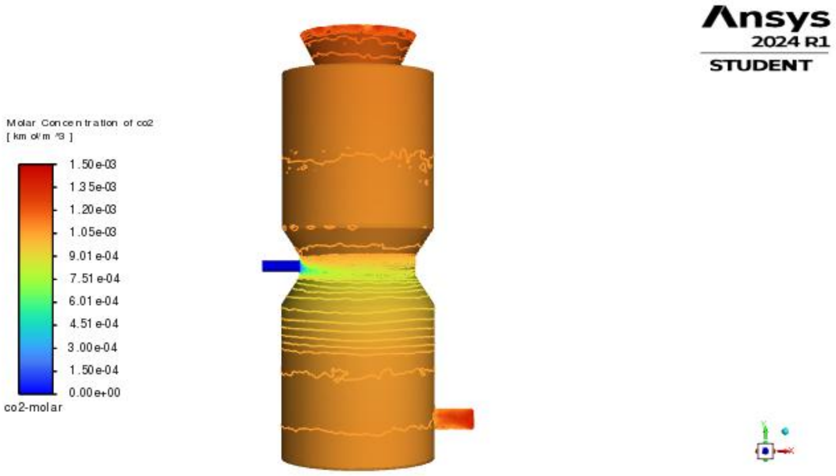


Figure 3.4c: Oxygen molar concentration

3. Finally, the mole, mass fraction and molar concentration of CO_2 are also shown below.







The results shown above are in consistent with those obtained by researchers who employed varieties of analytical and semi-analytical methods in solving the model gasifier equations. However, this CFD approach helps obtain the results accurately with high speed. The approach can also be employed in the event that the gasifier has a complex model with rigorous boundary conditions.

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