Modelling and Experimental Study of a Throat Updraft Gasifier Utilizing Corn and Wheat Straw for Syngas Production

Tafari Afessa Moroda

A Thesis Submitted to the Department of Mechanical Engineering

College of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfilment of the Requirement for the Degree of
Master of Science in Thermal Engineering

Office of Graduate Studies

Adama Science and Technology University

June, 2025

Adama, Ethiopia

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DECLARATION

I declare that this Master's Thesis entitled **"Modelling and Experimental Study of a Throat Updraft Gasifier Utilizing Corn and Wheat Straw for Syngas Production"** is my own work and has not been submitted to any university for a similar purpose. The references used in this thesis are duly recognized by proper citations.

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Dr. Dawit Gudeta

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Department	Mechanical Engineering
College	CoMCME
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We, the undersigned, members of the Board of Examiners of the thesis by Tafari Afessa have read and evaluated the thesis entitled "**Modelling and Experimental Study of a Throat Updraft Gasifier Utilizing Corn and Wheat Straw for Syngas Production**'' and examined the candidate during open Defense. This is, therefore, to certify that the thesis is accepted for partial fulfilment of the requirement of the degree of Master of Science in Thermal Engineering

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ACRONYMS

Symbol	Description	Symbol	Description
CC	Corn cob	SV	Superficial Velocity
CFD	Computational Fluid Dynamics	TEM	Thermodynamic Equilibrium Model
DDPM	Dense Discrete Phase Model	TES	Thermal Energy Storage
ER	Equivalence Ratio	TLUD	Top-lit Updraft
HHV	High Heating Value	TLUG	Top-lit Updraft Gasifier
LHV	Low Heating Value	PG	Producer Gas
MC	Moisture Content	RMSE	Root Mean Square Error
MFNN	Multilayer Feedforward Neural Network	WS	Wheat straw

NOMENCLATURES

Symbol	Description	Units
x_j	Mole fraction of individual species in syngas	--
$y_1 - y_5$	Number of moles of H_2, CO, CO_2, H_2O and CH_4	Mole
R	Universal gas constant	KJ/kmolK
$LHV_{biomass}$	Lower heating value of biomass	MJ/Kg
LHV_{syngas}	Lower heating value of producer gases	MJ/Nm^3
$C_{p,j}$	Specific heat of producer gas	KJ/kmolK
K_1 and K_2	Equilibrium constants of methane formation and water gas shift	--
Ex_{chem}	Chemical exergy of syngas	KJ/kmolK
Ex_{phy}	Physical exergy of syngas	KJ/kmolK
$Ex_{biomass}$	Exergy of biomass	KJ/kmolK
Ex_{gas}	Exergy of gasifying air	KJ/kmolK
Ex_{total}	Total exergy of H_2, CO, CO_2, CH_4	KJ/kmolK

ABSTRACT

Throat updraft gasifiers are typically employed to yield syngas with less amount tar formation. But, their syngas quality and efficiency were more influenced by biomass types, employed within systems. Because they needed long time was determined the performances of gasification system with all types of exist biomasses below different parameter, fast simulation techniques with proven numerical model were needed for the effective and economically use of energy resources. The theoretical studies were performed by different conditions after reviewing the previous research for this study. For the analysis of the performance of type biomass feedstock gasifier, thermodynamics equilibrium model was adopted. Corncob and wheat straw, which are locally available biomass wastes, were utilized for experiments. The effect of different parameters like moisture content, gasification temperature, and equivalence ratio of gasification system, were conducted. The Method attained this thesis was as per the set objectives. Biomass application in minimized size and formed densify, and air supply systems pressured was investigated experimentally in gasifier. The proximate analysis of wheat straw was 6.03% MC, 73.24% VM, 10.85% FC and 9.89% AC and for Corn cob 6.18% FC, 76.85% VM, 12.97%, FC, and 3.99% AC. It indicated that experimental study and the theoretical results concurred well. The model calculation of the system used corncob had higher exergy efficiency of 74.4% and wheat straw had 72.9 %. The temperature profile of gasifier had influenced by the biomass size to generated producer gas with desirable flame characteristics by gasification of biomass, for selected agricultural residues qualified biomass. The syngas produced from wheat straw production 20.78% H_2, 19.31% CO, 13.26% CO_2 and 0.68% CH_4, with calorific value *13.70 MJ/Kg, and from corn cob, 21.1% H_2, 23.35% CO, 12.62% CO_2 and 0.21% CH_4 and its 16.73MJ/kg. These results support the viability of using locally available biomass as sustainable feedstock for localized energy production through gasification.*

Keywords: *Feedstock, Gasification, Syngas Composition, Throat updraft*

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

The basic requirements for survival of man are Food, attire, shelter, and oxygen. But, since the world has increasingly industrialized at a fast pace, a part of these basic requirements need energy to be synthesized, produced or manufactured. It would not be wrong to state that survival of man depends upon Energy. Talking about Energy, the first thought is the energy derived from fossil fuel. The three main sources of energy are Crude oil, Coal and Natural gas (Zou et al., 2016). Whereas crude oil is animal origin, coal and natural gas are vegetable matter origin subjected to the extreme temperatures of the earth's crust for thousands of years. As seen from the source of these three, they are all non-renewable and once used up, can never be reused again.

This non-renewability of fossil fuel leads us to the problem of exhausting these resources. To overcome these problems scientists and researchers have come out with a series of alternatives which are renewable energy sources. Few of them are wind power, solar power, geothermal power, energy from biomass, etc. These sources even though are an alternative, had not been used to the extent that they have proved to be cost-effective. Biomass is a desirable environmentally friendly alternative renewable energy source in the context of current energy scenarios (Tiruye et al., 2021). Biomass has been confirmed as a source of a wide variety of useful chemicals and fuels. Historically, biomass has been one of the prevailing domestic's energy source in Ethiopian. Biomass serves the cooking energy needs of most rural households and a half of the urban house's requirements.

The Energy of biomass potential of Ethiopia is significantly and different resources to contributed to the all capacity. Wood biomass has most abundant around 74 Mton/year but it used only 81%, and crop leftovers has 38 Mton/year but 12.64% only used. Similarly, animal dung 29.8 Mton/year however 23,49% utilized per year. Therefore, Ethiopia has biomass potential amount 141.8Mton/year while 49.3% of those biomasses were left over without any consideration (Benti et al., 2021). Massive amounts of biomass are generated from agricultural field annually. These products have been inadequately utilized and managed or were allowed to rot or were burned in fields or discarded in the environment such as water bodies

(Bhuvaneshwari et al., 2019). Biomass has been combusted by domestic use in place of firewood on inefficient open fireplace stoves. But direct combustion such an energy resource to be used as a source of energy is inappropriate since it consists of low-density, high smoke, and low energy intensity.

Therefore, such resources are best used in the modern era using methods like gasification. Gasification is converting biomass in to gaseous fuels. The technology used in the process is to heat the biomass into fuel gas, where the gas produced can be either of low, medium or high calorific value depending on the gasification process utilized. Besides its use as a new means of supply of energy to residential places, the existing new factories in Ethiopia can have their energy needs partly met through gasification of biomass wastes in order to generate efficient service (Diriba Guta, 2012). It is well known that industries produce an appreciable amount of residue biomass in the form of a corn cob, wheat straw, bagasse, wood and other agricultural wastes.

All these wastes are used as a feed for the gasification reaction resulting in a syngas that can be used in powering engines and boilers, as well as increase the temperature of working fluids of turbines. Producer gas production by gasification is partial combustion of solid fuel (biomass) and takes place at temperatures above 700℃. A reactor is referred to as a gasifier. Combustion of biomass in complete form yields products that are composed predominantly of nitrogen, water vapor, and carbon and surplus of oxygen (if there is surplus air supplied). They are produced by reaction of carbon dioxide and water vapor through a glowing charcoal layer. Therefore, the key to gasifier design is to create conditions such that biomass is reduced to charcoal and charcoal is reduced at suitable temperature to produce carbon monoxide and hydrogen.

There are two type of gasifiers, fixed bed and fluidized bed gasifier. Bubbling Fluidized-Bed (BFB) and Circulating Fluidized-Bed (CFB) are the two major types of fluidized bed gasifiers. There are three main types of fixed-bed gasifiers: Cross draft, Downdraft, and Updraft. An updraft gasifier is a type of biomass gasification system in which fuel is fed from the top while air or oxygen enters from the bottom (Ismail and El-Salam, 2017). As the fuel descends, it passes through different temperature zones, leading to a series of reactions. At the bottom, where air enters, the highest temperatures are reached, facilitating combustion. A downdraft gasifier is a type of gasification system in which both fuel and air enter from the top, and the produced gas exits from the bottom. In this setup, the fuel moves downward as it undergoes drying, pyrolysis, combustion, and reduction in sequential zones. A cross-draft gasifier is a type of gasification system where the air flows horizontally across the fuel bed, contrasting with the vertical flow in updraft or downdraft gasifiers.

1.2 Working Principle of Throat Updraft Gasifier

Throat updraft gasifiers operate on the basis of two phases systems, which are systems in which both gas and solid phases coexist. For gasification to occur effectively in these systems, the solid biomass and the gasifying agent usually steam, oxygen, or air must interact. The throat area of a throat updraft gasifier’s design is crucial to improving the gasification process (Vyas, 2021). Biomass is inserted at the top of reactor; and it downward through different temperature profiles in the gasifier zone such as drying, pyrolysis, oxidation, and reduction (Abubakar et al., 2019).

Injecting the gasifying agent from the bottom causes it to rise through the biomass, forming a counter current flow that promotes effective heat transfer and reaction kinetics. The gasifier’s throat region was designed specifically to maximize flow dynamics. As the gaseous reactants pass throughout this narrow region, their velocity is increased by its convergent divergent configuration (Kaneesamkandi et al., 2023). A more efficient conversion of biomass into syngas results from this velocity increase, which also improves mixing and interaction between the solid biomass and the gas phase. In order to produce high quality syngas with a decreased percentage of tar, important reactions, including the change of the water-gas and cracking of the tar, are facilitated by the temperature of the region, which can rise to 750 °C (Vyas, 2021).

1.3 Statement of the Problem

Updraft gasifiers are widely used for biomass gasification due to their simple design, low operating cost, and ability to handle high moisture content feedstocks. However, one of the critical challenges in updraft gasifiers is the excessive production of tar and char, which significantly reduces the efficiency and quality of syngas. Despite various attempts to mitigate these issues, there remains a need for design-based interventions that can effectively minimize tar and char formation while enhancing syngas yield and quality. This research addresses the issue by improve the conventional updraft gasifier design with a throat addition, aiming to improve the internal flow dynamics and temperature distribution to achieve cleaner and more efficient gasification.

1.4 Objective

1.4.1 General Objective

The general objective of this thesis is to model and experimental study of a throat updraft gasifier utilizing corn and wheat straw for syngas production.

1.4.2 Specific Objectives

The specific objective of this research is;

- Model and simulat systems of gasification numerically
- Analyse the effect of ER, MC, and GT on performance of gasifier
- Analyse the temperature distribution and variation inside the gasifier during operation
- Analyse the quality of the gas produced from corn cob and wheat straw use as feedstock.
- Validate by comparing the experimental and numerical results

1.5 Significant of the Study

This thesis work has been carried out has great benefits as it produces syngas that can be utilized in fuel or generators. Additionally, this high-quality gas offers numerous advantages, including savings in time and cost require to obtain fuel, reduction in biomass usage, and minimize impact on forest and energy resources. The outcomes of this research will be beneficial for waste management, fuel production, environmental quality, and public health. This research will be included implementing syngas as a sustainable fuel source, particularly in rural areas.

1.6 Scope and Limitations of the Study

This research's aims involve designing, analysing, and validating experimental and numerical results for an updraft gasifier with a throat. How biomass type, syngas quality and exit temperature, equivalence ratio, ash, and moisture content all affect performance has been discussed. Using the appropriate methods and tools, this study was only analysing the producer gas's quality, composition, and another characteristic. In addition, no further study has been conducted on how to store the produced syngas for later use.

1.7 Organizations of the Research

There are seven chapters in this research and each one significantly contributes presentations of the research. The first chapter introduces the study's background, including discussions on biomass gasifier, identified objective, problem statement, scope of the study, and improved biomass gasification. The second chapter reviews related literature and identifies research gaps. The third chapter describes the materials and methods used in designing and developing the throat updraft gasifier to produce syngas. Chapter four discusses thermodynamic equilibrium model and gasifier design. Chapter five explained how to fabricated prototype of throated updraft gasifier and sample preparation for experimental analyses and its procedure. Chapter six presents the result and discussion of the thesis. The final chapter concludes the work and proposed recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Over View

This chapter covers fundamental details regarding the use of gasification technology in recent years. This section included reviews of works on the principles of biomass energy, various gasifier types and their application areas, previous studies on the design and operation of updraft gasifiers, concepts of simulation models for biomass gasification, the impact of various parameters in the gasification process, gasification mediums, bed materials, and the composition of the gas produced by biomass gasification. Finally, includes a summary of all the literature and its gaps.

2.2 Basic Principles of Biomass Energy and Conversion

The biomass referred to renewable organic matters produced by plants and animals. During photosynthesis, plants received CO_2 from atmosphere and ground water to form carbohydrate that form the biochemical structure of plant biomass. Plastic bags and agricultural waste are simply two examples of the diverse components that make up biomass. Biomass that produces energy contains alcohol fuels, landfill gas, industrial waste, wood biomass, and agricultural goods.

The availability, affordability, and relative homogeneity of woody or lignocellulosic biomass make it one of the greatest feedstocks for energy production. Cellulose (40–50%), hemicellulose (20–25%), and lignin (20–25%) are the three organic polymers that make up wood. Certain volatiles and mineral materials (1–15%) by weight percent are also present. Many types of energy can be produced using biomass. It can be burned directly to generate heat, and the flue gases that generate during the burning of biomass can be used to provide energy in different forms (Balat, 2006).

Direct combustion, the original biomass conversion process, is still widely utilized at a variety of scales, from small (for cooking and heating in the home) to large industry (for producing heat and electricity on different scales up to hundreds of MW power). The many conversion technologies that are utilized to extract biomass energy and transform it into a more usable form are referred to as biomass energy technology. The main solid waste conversion processes can be put into three different categories: thermochemical, physicochemical and biochemical each having the objective of converting solid materials to an energy (biological) conversion process (Sarker et al., 2024). As their names indicate, these methods aim to exploit, respectively, thermal, biological, and physical properties of solid waste materials.

Among the conversion paths, gasification represents one of the most promising technology for converting biomass into a fuel; it is a relatively clean process that may be generate syngas, which can be used as a fuel. The energy from biomass has solved two fundamental problems that plague other forms of renewable energy, such as solar and wind power: the of storage energy and the capacity of producing energy when it is needed (Adeniyi et al., 2023). The thermal design of a biomass utilization system, whether it is a gasifier or a combustor, necessarily needs the composition of the fuel as well as its energy content. The two types of compositions listed below are typically utilized in thermal conversion contexts such as combustion analysis:

Proximate analysis: Proximate analysis, which defines the biomass into gross components including moisture, volatile matter, fixed carbon, and ash, determines the biomass's composition.(Lei et al., 2023) ;(Manrique et al., 2019).

Table 2:1 Samples of biomass for proximate analysis (% Weight) with their HHV Value (in MJ/Kg (Saputro et al., 2018) ;(Kpalo et al., 2020).

Sample	Moisture%	Volatile%	Ash%	Fixed Carbon%	HHV (MJ/kg)
Corn Cobs	9.27	74.39	2.42	13.92	16.13
Wheat straw	13.37	72.27	3.27	13.09	16.19
Rise husks	12.67	68.2	16.1	15.7	15.18

Ultimate analysis: The hydrocarbon fuel's composition is stated in terms of its basic constituents (C, H, O, etc.), with the exception of moisture and inorganic elements include ash.

Table 2:2 Ultimate analysis of biomass samples (% Weight) (Kpalo et al., 2020)

Samples	C%	H%	O%	N%	S%
Corncobs	42.7	6.49	50.41	0.25	0.05
Wheat straw	41.42	6.02	50.83	1.2	0.13
Rice husks	45.2	5.8	47.77	1.02	0.21

2.3 The Fundamentals and Applications of Biomass Gasification

Gasification thermal process is converted drying biomass waste into mixtures of gas for burning in internal combustion engine and gas turbine. Type of biomass feedstock can be taken to considering while choosing gasification technology to improve output and minimized environmental effect. Through it closely relate thermochemical process gasification and combustion different significant. Gas is stored energy in gas chemical bond which was broken down by combustion for released energies. The process of gasification is added H_2 and sprit C from hydrocarbon biomass for produced gas with a high hydrogen to carbon ratio, while the combustions of oxidized hydrogen carbon in to H_2O and CO_2 respectively (Bhardwaj et al., 2019; Bhaskar et al., 2011).

2.3.1 Biochemical Conversion

Biochemical conversion is a significant and effective process for producing of biomass derived fuels chemical and material (Sarker et al., 2024). The biochemical conversion pathway includes processes that involve natural breakdown, which can be intentionally induced by the activity of bacteria or enzymes. As an instance, fermentation, anaerobic digestion, or enzymatic hydrolysis can all produce bioethanol.

2.3.2 Physicochemical Conversion

While moisture and volatile chemicals are eliminated, a solid product known as biochar or bio-coal is produced. This product is frequently utilized as fuel for power generation or in cofiring with coal. Physicochemical conversion uses combined physical and chemical mechanisms to change the structure of biomass.(Ghodake et al., 2021).

2.3.3 Thermochemical Conversion

Thermochemical conversion is a process that involved drying, pyrolysis, oxidation and reduction to convert biomass to energies which used for heat, electricity, and fuel transportation (Sarker et al., 2024). In efficiently utilizing biomass and waste materials, reducing reliance on fossil fuels, and addressing waste management issues. This technology significantly an important role in the production of sustainable energy. Combustion is thermochemical processes between biomass combust with O_2 to produced light and heat. Thermochemical conversion is the most common process for converting chemical energy stored in fuels into usable thermal energy, regularly used in power plants, engines, and heating systems.

The efficiency and environmental affected of combustion depend on factors such as type feedstock, gasification temperature, moisture content of feedstock, and oxygen availability. While gasification is widely used for energy production, it also reduced pollutants like NO_x and particulate matter, production it crucial to employ technologies that decrease emissions and improve efficiency (Leckner, 2015).

2.3.4 Gasification Reactions

Hydrocarbons in fuel, steam, CO_2, O_2, and H_2 in the reactor, as well as chemical interactions among the evolved gases of these, are all involved in the gasification process; the most significant of these is char gasification. It contains a certain amount of hydrocarbon comprising hydrogen and oxygen (Ismail and El-Salam, 2017). Char from biomass undergoes numerous reactions with the gasifying media throughout the gasification process. Among the reactions, the char-oxidation and partial-oxidation reactions are slowest, and consequently the rate controlling factor in the overall gasification process. This reaction is irreversible that represent the oxidation of char with oxygen and the heat released by these reactions drives subsequent processes (Mehta & Richards, 2017).

2.4 Classification of Biomass Gasifiers

Gasification systems can be classified as fixed bed, and fluidized bed, gasifiers based on the design of the reactor (Loha et al., 2018).

2.4.1 Fixed Bed Gasifier

In a fixed bed gasifier, the gas and gasifying media go up or down a bed of solid fuel particles.It is the simplest type of gasifier consisting of usually a cylindrical space for fuel feeding unit, an ash removal unit and a gas exit (Loha et al., 2018); (Corbetta et al., 2020.) Fixed bed gasifiers can be divided into three different categories: updraft, downdraft, and cross-draft (Loha et al., 2018).

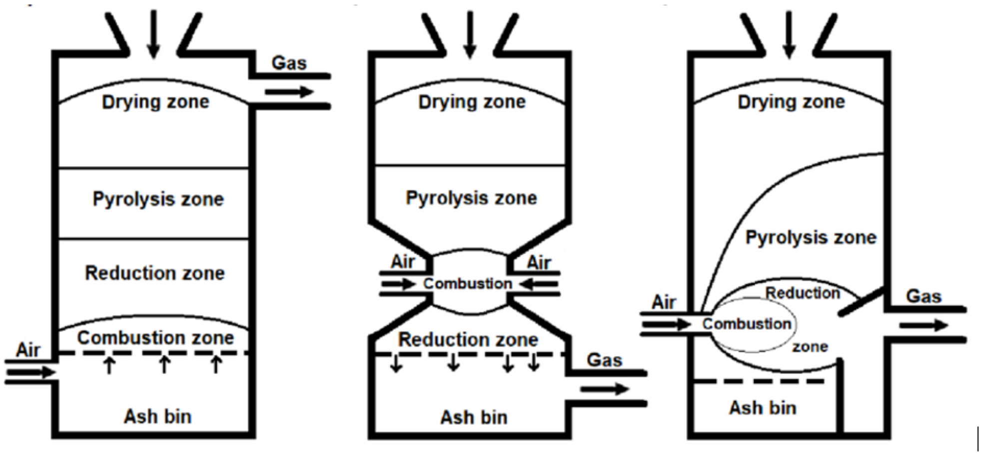

Figure 2.1 Thermo chemical and biochemical conversion (Ahmad et al., 2016).

2.4.1.1 Updraft Gasifier

The movement of the feedstock and the gasifying agent are in reverse directions in this type of gasifier (also called a counter-current gasifier). The tar concentration of the syngas from this gasifier is medium. On the other hand, the temperature of syngas exiting from this gasifier and hence the thermal efficiency of this type of gasifier is high (Ismail & El-Salam, 2017).

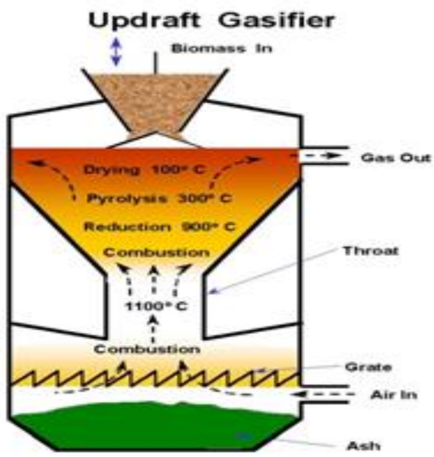

Figure 2.2. Schematic diagram of throat type updraft gasifier (Havilah et al., 2022)

2.4.1.2 Downdraft Gasifier

Both the feedstock and the gasifying agent go in the same direction in a downdraft gasifier. The gases have to pass through the high-temperature so amount of tar is significantly low (Saputro et al., 2018; Susastriawan et al., 2017).

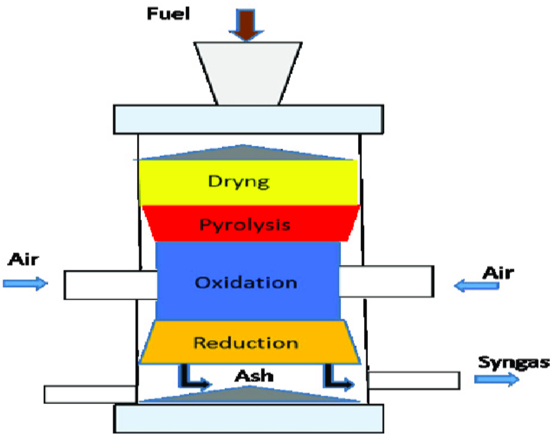

Figure 2.3 Schematic diagram of downdraft gasifier (Akhator et al., 2019)

2.4.1.3 Cross draft Gasifier

A cross-draft gasifier is a type of gasification system where the air flows horizontally across the fuel bed, contrasting with the vertical flow in updraft or downdraft gasifiers. This design allows for rapid heating and combustion, making it suitable for smaller-scale operations and for fuels with low ash content, such as wood or charcoal.

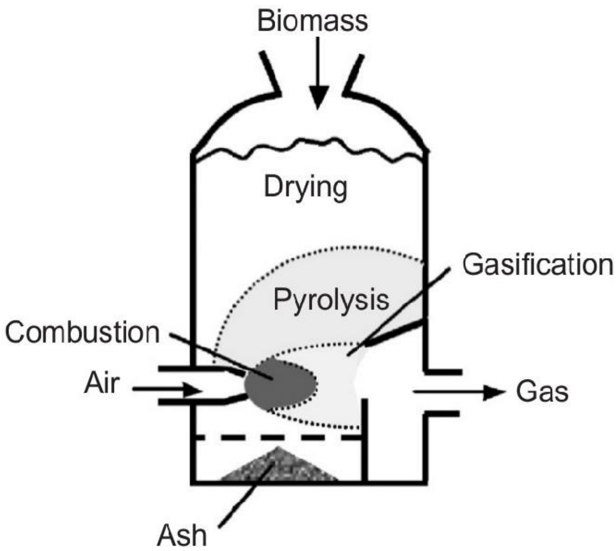

Figure 2.4 Schematic of a cross draft gasifier (Cerone et al., 2020)

2.4.2 Fluidized Bed Gasifier

Fluidized-bed gasification was initially developed to address operational issues with fixed bed gasification of fuels with high ash content, it can generally be used for large capacities (more than 10 MW). An alternating fluidized-bed heated sand bed and a suspended (bubbling fluidized-bed) sand bed receive the fuel. Two other categories of fluidized bed gasifiers are bubbling and circulating. Circulating fluidized bed adds one more feature to bubbling bed such that solid material trapped in the gas phase is trapped and recirculated back to the gasification bed. This lowers particle concentration in the syngas output and offers notable advantages over bubbling bed gasifiers in terms of mass conversion efficiency (Jarullah et al., 2017).

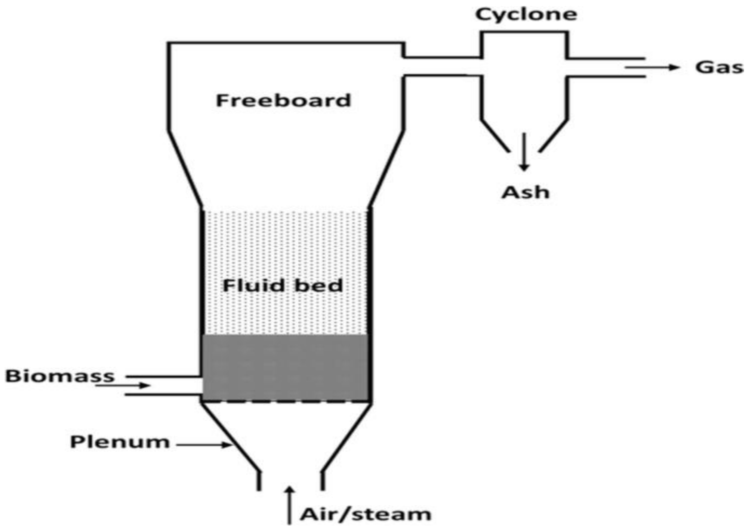

Figure 2.5 Schematic of a fluidized bed gasifier (Jarullah et al., 2017)

2.5 Throat Updraft Gasifiers

The throat updraft gasifier is the simplest kind of gasifier. The biomass is feed from the top of gasifier, while air injected at the bottom parts. Biomass is first dried by going through a drying zone as it drops. In the reactor zone, biomass decomposes and transforms into organic char and volatile gases. As the gasses and char moved through the reduction zone, they were further transformed into hydrogen and carbon monoxide. The heat generated by combust the char in the oxidation zone which is transferred up by the flowing gas because some of the char settles down in the reactor's bottom, powers the pyrolysis and drying processes. Char also releases carbon dioxide and water vapor as it burns (Bhaskar et al., 2011).

I) Drying zone: Biomass is fed into the top-mounted updraft gasifier, and by using the heat generated by some of the fuel wood partially burning in the combustion zone, the moisture content of the wet biomass is decreased. This is followed by the creation of water vapor in the drying zone, as demonstrated by the chemical analysis Equation 2-1 (Cerone et al., 2020).

$$M f + Q_s \rightarrow Df + H_2O \qquad \text{2-1}$$

Where, *Mf*, Q_s, and *Df* are Moisture of feedstock, Heat supply and dry basis feedstock respectively. The H_2O vapor descends and mixes with other vapors from the oxidation zone. The remaining is converted to hydrogen and becomes moisture in the gas.

II) Pyrolysis zone: Pyrolysis is the process of heating raw biomass without the presence of air. During this process, biomass degrades into char, different gasses, and liquids. This process, also referred to as breakdown, results in the release of volatiles. The products of pyrolysis depend upon temperature, pressure, residence time and heat losses. Pyrolysis, which occurs between 280 and 500°C, creates gases comprising carbon dioxide and tars. Complex bonds between H, C, and O molecules are the products, which are classified as volatiles. The products of this process are fixed carbon, or char, and tar, which are liquid, sticky materials (James et al., 2022).

$$Df + Q_s \rightarrow Char + Volatile \qquad 2\text{-}2$$

III) Reduction zone: Within a gasifier's reduction zone, a number of reduction reactions occur; the most widely used for these reactions are the water shift reaction Equation 2-3, Boudouard reaction Equation 2-4, and methanation reaction Equation 2-5.

$$CO_2 + H_2O \longrightarrow CO + H_2 \quad \Delta H = 40.90 \text{ kJ /mol} \qquad 2\text{-}3$$

$$C + CO_2 \longrightarrow 2CO \quad \Delta H = 159.90 \text{ kJ/mol} \qquad 2\text{-}4$$

$$C + 2H_2 \longrightarrow CH_4 \quad \Delta H = -87.50 \text{ kJ/ mol} \qquad 2\text{-}5$$

The amount of oxygen flow in the gasifier, the size of the feedstock, the moisture content of the feed biomass, and the volume of the reduction zone all affect the final composition of the synga (Al-Zareer et al., 2018). Residence time and reactor temperature can also affect the producer gas composition. The production gas composition may also be affected by residence time and reactor temperature. At high temperatures and low pressure, the heterogeneous endothermic process shown in Equations 2-3 and 2-4 can increase the amount of CO and H_2 (James et al., 2015). Conversely, low temperatures and high pressures favor the methanation reaction depicted in Equation 2-5 (Al-Zareer et al., 2018).

IV) Combustion zone: Heat is produced as the biomass partially burns. Only 25% of the O_2 required for full combustion is needed for this heterogeneous chemical reaction (Adeniyi et al., 2023). Exothermic carbon-oxygen reactions occurring within the combustion zone are depicted in Equations 2-7 and 2-7. Instead of CO and H_2O, which are byproducts of full combustion, a partial oxidation yields CO2 and CO. (Al-Zareer et al., 2018) state that the reduction and pyrolysis zones' endothermic reactions consume the heat created in this zone.

$$C + O_2 \longrightarrow CO_2 + 393.8\text{kJ/mol} \quad 2\text{-}6$$

$$C + 1/2O_2 \longrightarrow CO + 123.1\text{ kJ/ mol} \quad 2\text{-}7$$

$$C + H_2O + 118.5\text{kJ/mol} \longrightarrow H_2 + CO \quad 2\text{-}8$$

Equation 2-8, illustrates the water-carbon interaction, which is an endothermic reaction between carbon in the combustion zone and moisture in the air; CO and H_2 are the products of this reaction.

2.6 Factors Affecting Gasification Process Performance

The effectiveness of the gasification process is influenced by various factors across all types of gasifiers. Key variables include the type and size of biomass, the rate at which the biomass is fed into the system, and the ash content of the material. Other important factors are the equivalence ratio (ER), moisture content (MC), and the residence time of the feedstock in the gasifier (Cerone et al., 2020). Additionally, the superficial velocity (SV) and the choice of gasifying agent also play significant roles in determining the overall efficiency of gasification process (Adeniyi et al., 2023).

2.6.1 Effect of Biomass Type

The elemental concentration of biomass has a significant effect on syngas composition. The ratios of H_2 to C and O_2 to C are essential for the release of pyrolysis gas, and they increase as these ratios are, particularly when the H_2 to C ratio increases. Because of the oxygen that is naturally present in biomass, a high oxygen concentration requires low ER for gasification (James et al., 2022).

2.6.2 Effect of Particle Size

In an updraft gasifier, the optimal particle size for the biomass feedstock is typically between 2mm and 6mm; with larger particles (around 6mm) being preferred to minimize the amount of fine dust and promote better gasification efficiency, while still allowing for proper air flow through the bed (Feng et al., 2011).

2.6.3 Effect of Volatile Matter

An indicator of the concentration in organic hydrocarbons in biomass is the volatile component of solid fuel. In addition to determining the quantity of fuel generated, this measurement also helps in determining the biomass feedstocks ignite and thermal conversion capabilities. On the one hand, the temperature of gasification has an effect on syngas related to the volatile content. A high gasification temperature can cause the volatile material to be secondary Pyrolyzed into low-molecular gases like H_2, CO, CH_4, and other, increasing the yield of syngas.

According to (Gao et al., 2023) Raising a gasification temperature between 600 to 750 ^{0}C facilitates conversion of tar into syngas species as, CO, H_2 and CH_4. This result to notables to a reduction in tar production 4.6% and rise in the overall gas produce. During the gasification process, biomass is pyrolyzed and gasified concurrently, with pyrolysis progressing faster than gasification. The volatile matter content in the biomass plays acritical role as higher volatile contents enhances the impact of pyrolysis on syngas production. It is vital to notice that biomass with high volatile content generates more gas during pyrolysis with CO is dominated gas components. When volatile content is high fixed carbon content is typically lower. As a results hydrogen content in producer gas is decrease as increasing volatile matter while, CO concentration is raise-with volatile contents.

2.6.4 Effect of Equivalence Ratio

The proportion of actual O_2 supplied to fuel to the O_2 required for complete combust of theoretical biomass to fuel is defined as the ER. Additionally, to directly influencing the relationships between the biomass fed rate and the supply rate of the gasifier, the equivalence ratio also effects the calorific value, gas components, reactor temperature, and pressure. The feedstock, gasification agent, and gasifier all affect the equivalence ratio (Gao et al., 2023). Combustible gas concentrations (H_2, CO, CH_4, and tars) reduce as equivalence ratio rises, but CO_2 is level rise accordingly. equivalence ratio increases give the gasifier a large amount of oxygen, which it uses to oxidize CO, H_2, CH_4, and tars. O_2 is used in the oxidation and methanation reactions to convert CH_4 to CO and H_2O, while hydrogen is converted to H_2O (Kumar et al., 2023).

Further, other light hydrocarbons such C_2H_2, C_2H_4, C_2H_6, and C_3H_8 (Silva et al., 2019) that are produced during the gasification process are neglected. The literature's recommendations for optimal equivalence ratio differ according on the type of gasifier and feedstock.

$$ER = \frac{0.21 n_{\mathrm{air}}}{n_{\mathrm{C}} + 0.5 n_{\mathrm{H}} - n_{\mathrm{O}}} \quad \text{2-9}$$

where the molar amounts of C, H_2, and O_2 in biomass are denoted by n_C, n_H, and n_O, respectively, and n_{air} is the molar amount of air required for gasification (Karamarkovic and Karamarkovic, 2010). According to some researches are conducted, the values of equivalency ratio ranged from 0.24 to 0.4.

2.6.5 Effect of Ash Content

Ash content is a crucial factor in gasification by affecting gasifier selection and configuration. Gasifier are design to remove ash as either solid or liquid slag. Ash composition, containing alkali and alkaline earth metal, can be act as catalysts during thermal degradation (P. Wang and Massoudi, 2013). The amount and composition of ash plays a crucial role in gasification behaviour. The average ash percentage of the corn cob was least at 2.2%.(Anukam et al., 2017).

2.6.6 Effect of Moisture Content

During gasification of biomass the concentrations of moisture content is affected the amount of CO2, CO and H2. When the content of moisture in biomass is rise, the concentrations of CO2 and H2 is increase while CO is reduced. At higher temperatures, the direction tends to reverse, but the equilibrium constant for the water shift reaction varies little across a wide temperature range. Since more heat is required for moisture evaporation than the small amount of heat gained due to the exothermic behaviour of the water-shift reaction, thermal energy inside the gasifier reduces when gasifying biomass with higher moisture content. Higher moisture content has been seen to increase hydrogen content, decrease carbon monoxide, and increase methane, which has a very low percentage (Kumar et al., 2022).

2.6.7 Effect of Air Gasification

Gasification process used air as a gasifying agent is the most straightforward and widely utilized technique. A limited amount of air is used to burn the excess char produced by the gasifier's pyrolysis process. The generated syngas has a heating value between 2.5 and 7.5 MJ/Nm3, making it appropriate for use in boilers and engines. They combined three individual zones of pyrolysis, gasification, and combustion of biomass fuel in a gasifier (Kaneesamkandi et al., 2023). To keep the reactor's temperature high, secondary air was fed into the top zone. Syngas was created at a rate of 33 Nm^3/kg and had a heating value of roughly 5MJ/Nm^3 under optimal operating conditions.

2.6.8 Effect of Gasification Temperature

The gasifier bed temperature effects all of the chemical reactions that exist in gasification process. Rise in temperature reduces the tar content as well as decreases char inside the gasifier of syngas. Producer gas rise due to higher tar breaking down (Saleh and Samad, 2021). High temperature in gasification can raise syngas production, HHV, carbon conversion and cold gas efficiency. In an experiment conducted (Kumar et al., 2022), an increased in gasifier bed temperature from 700°C to 850°C, at a constant Equivalence ratio of 0.3, the composition of the syngas produced was changed. The temperature of the reactor is dependent on different factors such as MC of the fuel, ER, heat losses from the system, and amount of steam added. Therefore, the ideal compromise between ER and the gasifier's internal temperature should be represented (Nyoman Suprapta Winaya et al., 2018).

2.7 Simulation Models of Biomass Gasification

Several studies have focused on the modelling and analysis of biomass gasification processes. The models mainly use kinetic, thermodynamic, artificial neural network (ANN), and computational fluid dynamics (CFD) techniques to model all stages of gasification, such as pyrolysis, reduction, combustion, and drying (Sun et al., 2023). On the basis of energy and mass balances, thermodynamic models forecast the composition of syngas; on the other hand, kinetic models take reaction rates into account to more accurately depict the behaviour of biomass conversion in real time. To enhance conventional thermodynamic and kinetic model with a data-driven method, artificial neural networks (ANNs) can be used to anticipate the composition of syngas, optimize process parameters, and model the nonlinear correlations between operating variables and gasifier performance. The gasifier's mass transfer, heat, and fluid flow are all simulated in CFD models, which provide more information. In particular, in updraft gasifiers where the counter-current flow complicates the operation, these models are essential for enhancing performance, minimizing environmental impact, and optimizing design (Cerone et al., 2020).

2.7.1 Computational Fluid Dynamics (CFD)

CFD model is utilized to estimate the variation of the temperature concentration, and others key parameter with in a reaction. This mode depends on a simultaneous determination for a system of equations governing the mass, momentum, energy, and species concentrations across the defining region of the gasifier. CFD model can provided more accuracy prediction of temperature and gas produced with in the reactors. In biomass gasification, CFD modelling integrated both dense and particulate flow dynamics and complex chemical reaction.

(La Villetta et al., 2017) analysed experimental and computational fluid dynamics investigation to analysis the performance of a rice husk updraft gasifier using the various gasification agent. The study developed and validation a 1D mathematical model to forecast the temperature distribution, and gas composition with in reactors. The experimental data was used to examine the effect of MC and air fed temperature on performance of gasifier. The model accurately anticipated and validated the gas composition and temperature profiles across different operating condition, demonstrated that increasing air feed temperature improved gasification efficiency while moisture content reduce gasifier performance.

Using the simulated CFD model, (Lu et al., 2017) analysed the way carbonized wood briquettes gasify in an updraft gasifier. The study developed 2D unsteady mathematical model to predict the temperature distribution and syngas composition within reactor. The experimental findings were used to validate the model confirming its accuracy in simulating carbon conversion and gasification kinematics. Various process parameters including reaction zone, particle size, and variation of biomass were investigated.

(Sun et al., 2023) examined a study that used the dense discrete phases model with CFD model to estimate the functioning of an integrated updraft gasifier with thermal energy storage. Their research conducted various internal velocity, temperature and pressure within the gasifier, with an emphasis on the effects of MC and air to fuel ration.

(Gao et al., 2023) conducted a comprehensive Cyclone gasifier CFD model using the fluent software. It improves insight into gas temperatures distribution within the gasifier and syngas composition. The influences of the ER were analysed and validated through experimental data results indicated that carbon conversion ranged from 70% to 89.3% while cold gas efficiency varied 53.7% and 65% as ER was adjusted between 0.25 to 0.35. The highest LHV of the syngas measured 5.6 MJ/N*m* 3 was achieved when the ER was within the range of 0.25 to 0.28.

2.7.2 Artificial Neural Network (ANN)

(Yucel et al., 2019) conducted on ANN based model forecast biomass gasification products into fixed bed gasifiers. To determine the composition of syngas, ANN models and nonlinear autoregressive exogenous neural network models was constructed. The model used ER, air fuel rate temperature distribution and proximate and ultimate biomass properties as input parameters. The ANN models consisted of input layers, a hidden layers and output layers. Experimental gasification data comprising 3831 sample from pinecones and woody pellet gasification was used for training the validation achieved high accuracy with R^2 values exceeding 0.99. The best results were obtained using multilayer perception ANN and GBM regression effectiveness of machine learning in optimizing gasification process.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(X_{Actual} - X_{Predicted})2}{\sum_{i=1}^{n}(X_{Actual} - X_{Mean\ value})2} \qquad 2\text{-}10$$

In the Equation 2-10 R^2 is the type of evaluation metrics utilized by the machine learning model coefficient of determination, $X_{\text{Predicted}}$ is the value generated by the machine learning model, n is the number of times the machine learning model has been run and X_{Actual} is the value expected from the test dataset.

2.7.3 Thermodynamic Equilibrium Model (TEM)

The TEM is a crucial tool for analysing the performance of throated updraft gasifier which are designed to convert biomasses to syngas through a series of thermochemical processes. This model operates on the principle of Gibbs free energies minimization, allowed for the prediction of producer gas for drying, pyrolysis, combustion and reduction zone. In throat updraft gasifier biomass is introduced from the upper and move to down through these stages while, air is supplied from the bottom. The TEM facilitated the understanding of how different operational parameters as air to fuel ratio, gasification temperature, moisture content, and volatile matter affects the yield and quality of gas produced (Xu et al., 2021); (Cerone et al., 2020);

2.7.4 Kinetic Models

Designing, evaluating, and improving gasifiers involves information of the kinetic mechanisms describing the conversion during biomass gasification, which kinetic models provide (Corbetta et al., 2022). In this model, the gasifier reactor's hydrodynamics and the kinetic reaction of gasification inside the gasifier are combined. Due to the extremely slow reaction rate at low reaction temperatures, a lengthy residence period is needed for full conversion. Therefore, kinetic modelling is more suitable and accurate at relatively low operating temperatures 950 ^{0}C (Cerone et al., 2020).

Table 2:3 Advantage and disadvantage of different modelling methods

Modelling technique	Advantage	Disadvantage
Computational fluid dynamics (CFD)	-Provides a comprehensive understanding of the mixing, temperature distribution, and gas movement inside the gasifier. -Enables in the improvement of design components like fuel distribution, air intake, and throat shape. -Less costly physical experiments are required. -It makes it possible to visualize flow behaviour, which helps improve performance.	-Required high computational power and long-time simulation -It required accurate boundary condition -Complex setup and numerical instability
Artificial neural networks (ANN)	-predict syngas compassions, temperatures and efficiency depends on trial data -Do not required explicit mathematical equation -Can solve complex and nonlinear equation relationship in gasification process	-Need high quality of data set reliable prediction - Overfitting and underfitting may be occurred if has not properly trained - Trained need significantly computational effort
Thermodynamic equilibrium model (TEM)	- Simples and quicks calculation to estimates gas compositions and efficiencies - Need fewer parameters as compared with other models -Useful for determine theoretical improved syngas production	-Consider equilibrium which cannot be valid in throated updraft gasifiers due to incomplete reaction -Cannot accurately reflected real world condition at lower temperature
Kinetic Models	-Allow for studied transient behaviour conditions in dynamics gasification condition -Provided reaction rate analysis in syngas compositions	-Need extensive kinetic data which can be difficult to obtained - Model accuracy depend on selection of reactions mechanism

	-May helps to optimise residence times and required temperature for good efficiency	-Experimental validations are necessarily reliable prediction

2.8 Literature Review on Previous Works

The gasification of biomass has been addressed in several of ways by different researchers using modelling and experimental methods to increase the effectiveness and performance of updraft gasifier mechanisms.

(F. Sulaiman et al., 2019) investigated the influence of temperatures, time consumed and catalyst addition on composition of syngas produced from the updraft gasification of tobacco leaf wastes. A fixed bed reaction with 300 gm capacity was utilized with experimental conducted at 700 ^{0}C to 900 ^{0}C for 20 minutes. The effect of K_2CO_3 catalyst on syngas compositions were also examined. Gas chromatographs were employed for produced analysis, revealing that the highest concentrations of CO (22.83%), H_2 (23.46%), and CH_4 (3.23%) were obtained at 700 ^{0}C after 10 minutes. This study was conducted temperature, residence time, and catalyst presence significantly impacted gasification efficiency and product composition, gas with optimal condition enhancing carbon conversion and syngas quality.

(Corbetta et al., 2022) examined the calorific value, gasifier efficiency, and producer gas composition at various rates of biomass consumption through extensive trials. The maximum gasification efficiency (77.94%) was produced by maize cobs at a consumption rate of 5 kg/h, according to the results. Wood and sawdust briquettes came in second and third. Wood and maize cobs produced producer gas with greater calorific values, which made them perfect for energy generation. The wood also had the maximum thermal efficiency (30.65%) at 7 kg/h. As maize cobs emerge as the most attractive fuel source, the study's findings demonstrate the throat-type gasifier's potential to produce energy efficiently using a variety of biomass fuels.

(Vyas, 2021) examined sawdust briquettes, sized wood, and maize cobs to study a throat-type updraft gasifier. They experimented with various biomass consumption rates, paying particular attention to thermal efficiency, gas composition, and gasifier efficiency. With a maximum thermal efficiency of 29.60% percent at 8 kg/h, maize cobs demonstrated the highest gasifier efficiency of 77.94% at 5 kg/h. As consumption rates rose, the composition of the gas dropped.

(Sedej et al., 2022) conducted the effect of factors such as ER, temperature, and correlation factors of reaction equilibrium constant on syngas composition. The study utilized ANN for model validation and introduced new empirical correlation to predict the concentrations of CO, CO_2, CH_4, and H_2. Those researches indicated that the temperature, and ER played significant roles in determining syngas composition with high temperature favouring CO and H_2 production. The inclusions of correlation of factors improved model accuracy, reducing root mean square error (RMSE) to below 6%.

2.9 Literature Summary

The literature review states that throated updraft gasifiers have been modelled and assessed in order to determine the gasification system's performance under various conditions. The three main modelling approaches that was used to model the gasification process for forecasting the temperature and composition of producer gas were the thermodynamic equilibrium model, computational fluid dynamics, and kinetic model. While taking into consideration the following input parameters, the performance of the gasifier was also assessed using a range of biomass samples: biomass size, moisture content, equivalency ratio, steam to biomass ratio, gasification temperature, throated to gasifier diameter ratio, and air injected at nozzle placement. The estimated and observed impacts of those basic input parameters on the gasification temperatures, as well as the produce, composition, exit temperature, cold gas efficacy, and lower heating values of syngas, were validated by relevant literature.

Table 2:4 Summary of previous related work

Authors (Year)	Sample	Modeling Methods	Parameters	Outcomes
(La Villetta et al., 2017)	General biomass types	Thermodynamic Equilibrium Model	✓ ER rise from 0.2 to 0.4, ✓ Temp range from 800 to 1000 °C, ✓ Moisture range up to 20%	Producer gas composition range 20 to 25% H_2, 20 to 22% CO, 3 to 5% CH_4

(Silva et al., 2019)	Wood, straw, bagasse, sludge	Thermodynamic Equilibrium Model	✓ ER is 0.2–0.45, ✓ Temp is 700–1000 °C, ✓ Moisture is 5–20%	H_2 prediction improved by 15%
(Vyas, 2021)	Maize cobs, wood, sawdust briquettes	Experimental study	✓ ER range 0.25 to 0.35, ✓ Temp range 650–850 °C, ✓ Moisture range 8.2–10.5% (measured)	Compositions of syngas 21.30% CO, 16.7% H_2, 2.4% CH_4
(F. Sulaiman et al., 2019)	Tobacco leaf waste	Experimental investigation	✓ Temp: 700 to 900 °C, ✓ Moisture: 13%,	Syngas composition; 22.82% CO, 23.46% H_2, 3.23%CH_4
(Kumar et al., 2016)	Wood, Bagasse, Rice Husk	Thermodynamic Equilibrium Model	✓ ER: 0.25–0.45, ✓ Temp: 773–1130 °C, ✓ Moisture: 0–30%	✓ LHV (MJ/Nm^3): Wood 5.5 to 4.2, Bagasse 4.6 to 3.5, Rice Husk 4.2 to 3.2 ✓ Temp decrease from 1130 °C to 773 °C
(M. A. Sulaiman et al., 2019)	Corn Stalk, Corn Cob, mixture of corn cob with corn stack (50:50)	Experimental investigation	✓ Sun dried at ambient temperature 33 0C ✓ Moisture range 3% to 3.75%	✓ Determined ultimate analysis of feedstocks

2.10 Research Gap

A thorough review of previous studies indicates that many have focused on modelling and evaluating the performance of updraft gasifiers using various biomass feedstocks and parameters. It is clear from the review above that a gasification system's performance can be evaluated using a wide range of parameters. However, it has been found that most evaluations of the gasification system's performance rely heavily on the syngas composition and LHV in relation to the experimental results. The following gaps have been identified in the literature:

- Limited studies have examined geometric improvements that reduce tar and char development in updraft gasifiers by adding a throat.
- There is a lack of research on the producer gas flame intensity and characteristics for different biomass feedstocks. Understanding flame behavior can offer valuable insights into combustion stability and syngas quality.
- The relationship between throat design parameters and syngas quality improvements remains underexplored.

Therefore, in this thesis, an attempt will be made to fill the aforementioned research gap by an experimental and theoretical analysis.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Over View

This chapter presents the study's overall design, including the phases of the research as well as the method used to complete the task. The work done in each phase, as well as the tools, flow charts, and models utilized, have been all thoroughly discussed here.

3.2 Materials

The materials chosen for the production of syngas in the throated updraft gasifier must provide durability, cost-effectiveness, and high-performance during operation. Due to its strength, ease of manufacturing, and dependability in gasification processes, mild steel is used for the gasifier reactor and its stand. Stainless steel has excellent resistance to corrosion and durability; it is used for the air inlet pipe, gas outlet pipe, and cyclone gas inlet and outlet.

Table 3:1 Materials selected for throat updraft gasifier

S. No.	Gasifier part	Material selected
1	Reactor zone	Mild steel
2	Cyclone separator for gasifier	Mild steel
3	Reactor air inlet and PG outlet	Stainless steel hallows cylindrical bar
4	Cyclone PG inlet and outlet	Stainless steel hallows cylindrical bar
5	Gasifier Stand	Mild steel hallows rectangular bar
6	Flame line	Stainless steel hallows cylindrical bar

Different components of the gasification system were model using SOLIDWORK 2022 and the MATLAB as a computational tool.

In the throated updraft gasifier experimental study, several instruments will be used in order to ensure accuracy in measurements and maximum efficiency. These instruments are thermocouples, thermometers, oven, Hydraulic type pelletizer and Exhaust gas analyser. In order to optimize gasification conditions, the thermocouple is used to monitor the temperature at difference places within the gasifier. In addition to the thermocouple, a thermometer was also used for ambient temperature readings during the tests. A weighing scale was used for providing exact measurements of the biomass feedstock, enabling specific input amounts for the gasification process.

Table 3:2 Instrumentation measurements and their purpose

S. No.	Instrumentation	Purpose
1	Digital thermometer	Measured environmental temperature
2	Thermocouple	Measured distributive temperature
3	Exhaust gas analyser	Read the compositions of exhaust gas
4	Oven	Moisture content determination
5	Coffee grinder	Grinding CC and WS
6	Sieve	Particle size distribution
7	Hydraulic type pelletizer	Palletize of CC and WS

3.3 Methodology

The aim of this research is to convert biomass to gaseous fuel using a gasifier technology. Based on the objectives of the research, various methods are used to conduct and analyse the research. In this research, started with the preparation of biomass samples, design of combustion zone, throat, cyclone separator, grate, air injector, ash pit, and assembling and installing of updraft gasifier with throat, and numerical and experimental methods was also including. Based on the previous research, theoretical and experimental perspectives was explored to accomplish this task. Numerical approach, were made different governing equations. In addition, the study applies an equilibrium model of an updraft gasification process to evaluate how effectively an updraft gasifier works with locally sourced biomass materials like corn and wheat straw. A comparison and analysis of these calorific values of biomass will conduct in this experiment; and, data are presented on the basis of the work.

Further by using throat reduce the char content and increasing the syngas quality also, the analysis of the producer gas flame intensity corn and wheat straw as feedstocks in gasifier, by using thermocouple is used to monitor the temperature at various places with in gasifier. The parameters of the process are easily studied, besides the workflow was estimate using the method derive from thermodynamic equilibrium. The research involves working on the propose gasifier at various times and providing the necessary components for the research; tests were also conducted by difference parameters. Experimental studied was conduct and the effect of some parameters including type of biomass, MC, ER, pellet size, and gasification temperature on the performance of the gasifier to conduct.

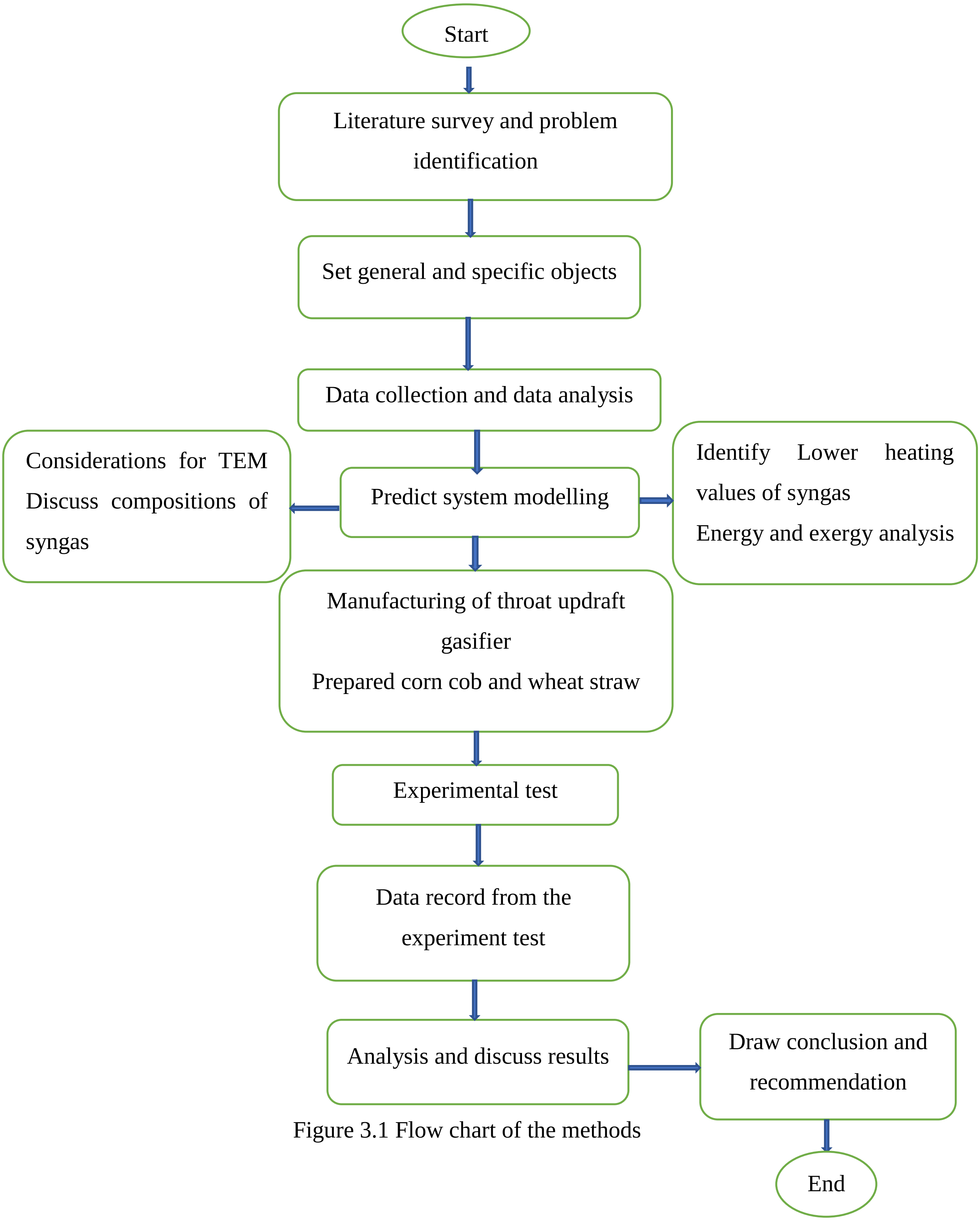

Figure 3.1 Flow chart of the methods

3.3 .1 Review of Literature

The process begins with a thorough review of existing literature on biomass gasification and its classification. This review explores a range of methods and techniques for modelling and designing gasification systems, as well as investigating different types of gasifiers, their selection criteria, and the appropriate gasifying agents. Both theoretical and experimental research are analysed to gain deeper insights. Information is collected from various research papers and journals on throat updraft gasifiers, focusing on factors that impact their performance, syngas composition, and essential design parameters.

3.3.2 Mathematical Model

An equilibrium thermodynamic model that predict the composition of syngas using stoichiometric thermodynamic technique used for evaluated the performances of throat updraft gasifier. The elemental composition of the biomass, along with moisture content and other operational parameters, were used to solve nonlinear equation derive from mass balance and equilibrium reactions. MATLAB was employed for these calculations, providing results on the producer gas composition and properties, including its LHV, under different operating conditions.

3.3.3 Experimental Methods

This investigation encompasses an analysis of biomass feedstocks such as corn and wheat straw and an assessment of the performance of a throat updraft gasifier prototype. The study employs experimental and numerical approaches to evaluate factors influencing gasification, including biomass size, moisture content, and equivalence ratio. A systematic methodology is adopted, integrating biomass preparation, reactor design, and performance testing to improve syngas production. Additionally, advanced monitoring tools, including thermocouples and analytical equipment, are used to measure temperature, composition, and gas quality across operational conditions.

3.3.4 Validation

Based on the equilibrium model and MATLAB iteration the product gas composition was predicted, these laid the base for evaluating the energy and exergy performance of gasifier.

Investigation of experiment was conducted to validate the model results. In addition, comparison of the syngas composition with other researchers was also made.

3.3.5 Data Analysis and Interpretation

Excel spreadsheet software and MATLAB were the basic tools utilized as data storing, analysis, and clarification tool for performance investigation of the throated updraft gasifier reactor and graphically show the effect of operating parameters during the experimental test.

CHAPTER FOUR

THERMODYNAMIC EQUILIBRIUM MODEL AND GASIFIER DESIGN

4.1 Over View

This chapter describes an overview of the thermodynamic equilibrium model for the research, including the formulation of the model, mass and energy balances, energy analysis, and model implementation. Additionally, a comprehensive literature review is used to ensure that the geometrical dimensions of the various components of the proposed gasifier are constructed using appropriate assumptions and data.

4.2 Thermodynamic Equilibrium models

Thermodynamic Equilibrium model predicts the final compositions of gasification products by assuming that all chemical reactions reach equilibrium. It calculated the most stable states of a system based on the minimizations of Gibbs free energy under given temperature conditions. This model is commonly used for preliminary analysis, offering insight into the maximum theoretical efficiency and product yield of gasification(Jha and Massa, 2021). The main thermodynamic equilibrium models are existing in the literature take in to account the following simplifying assumptions (La Villetta et al., 2017); (Fernando and Narayana, 2016):

- Ash and nitrogen are considered to be inert.
- Kinetic and potential energies are neglected.
- No oxygen in the gas produced.
- CO_2, CO, H_2, CH_4, H_2O, and N_2 are the only significant components that make up the gas that exits the gasifier.
- Consider dry air is contain 21% oxygen and 79% nitrogen in the combustion.
- Steady state is assumed.
- Assumed perfect mixing with uniform pressure and temperature.
- The contribution of ash to the energy balance equation is neglected.
- At 298 °K, the biomass feedstock and air enter the gasifier, which has a pressure of 1 atmosphere.
- It is assumed that the system is adiabatic and does not account for heat losses.
- The amount of tar produced by the gasifier is negligible.

- The biomass feedstock consists of carbon, hydrogen, oxygen, and nitrogen; and chemical formula of biomass is $CH_xO_yN_z$.

It is assumed that the formula of biomass chemical is $CH_xO_yN_z$.

$$x = \frac{HM_C}{CM_H}, \quad y = \frac{OM_C}{CM_O}, \quad z = \frac{NM_C}{CM_N} \qquad 4\text{-}1$$

C, H, O, and N are the mass-fraction, while M_C, M_H, M_O, M_N are the molecular weight of carbon, hydrogen, oxygen and nitrogen in biomass feedstocks respectively (Yan et al., 2018).

It is gasifier in m moles of air; the global gasification reaction can be written as follows:

$$CH_xO_yN_z + bH_2O + c\,(O_2 + 3.76N_2) = y_1H_2 + y_2CO + y_3CH_4 + y_4CO_2 + y_5H_2O + (1-\mu)\,C + (\frac{z}{2} + 3.76c)\,N_2 \qquad 4\text{-}2$$

where y_1, y_2, y_3, y_4, y_5 and $(1-\mu)$ are amount of stoichiometric coeffient of H_2, CO, CH_4, CO_2, H_2O and uncreated carbon respectively in the products. x, y, z are the mole ratio of H_2, O_2 and N_2 to C determined from ultimate analysis of the biomass.

$$b = \frac{MC \times (12 + x + 16y)}{18 \times (1 - MC)} \qquad 4\text{-}3$$

$$c = ER \times (1 + \frac{x}{4} - \frac{y}{2}) \qquad 4\text{-}4$$

$$\mu = 0.32 + 0.84 \times (1 - \exp\left(\frac{-ER}{0.299}\right)) \qquad 4\text{-}5$$

The overall balancing coefficient of reactions of C, H_2, and N_2 are expressed as

For Carbon: $y_2 + y_4 + y_3 = \mu$ 4-6

For Hydrogen: $x + 2b = 2y_1 + 4y_3 + 2y_5$ 4-7

For Oxygen: $y + b + 2c = y_2 + 2y_4 + y_5$ 4-8

The following are the major reactions that take place during the gasification process:

Boudouard reaction: $C + CO_2 \rightarrow 2CO$ +159.9 kJ/molK 4-9

Water gas or steam reaction $C + H_2O \rightarrow CO_2 + H_2$ +131 kJ/molK 4-10

Methane formation: $C + 2H_2 \rightarrow CH_4$ −87.5 kJ/molK 4-11

Water gas shift reaction: $CO + H_2O \rightarrow CO + H_2$ −41 kJ/molK 4-12

The phase rule should be used to determine the number of independent reactions in order to formulate an equilibrium model. Since equilibrium is thought to be reached while there are no solid carbons in the equilibrium state, only the two mains reactions the water gas shift and hydrogasification can handle it. Water gas shift reaction is one of the reactions happening during gasification process. It illustrates how CO and water vapor react to produce H_2 and CO_2.

It is commonly utilized to adjust H_2 to CO ratios in syngas. A similar procedure is used to determine the constant of Equilibrium K_1 of water gas shift reaction for any reactor temperatures. The equilibrium balance between producer gas species was described by independent reactions in the reduction zone. The water shift reaction Equation 4-12 with the equilibrium constant of K_1 was determined in Equation 4-13.

$$K_1 = \frac{y_{4*}y_1}{y_{2*}y_5} \quad \text{4-13}$$

$$\ln K_1 = \frac{5870.53}{T} + 1.86 \ln T - 2.7 \times 10^{-4} T - \frac{58200}{T^2} - 18.007 \quad \text{4-14}$$

The methane formation in Equation 4-11 equilibrium constant of K_2 was determined in Equation 4-14

$$K_2 = \frac{[CH_4]}{[H_2]^2} = \frac{\left(\frac{y_3}{y_T}\right)}{\left(\frac{y_1}{y_T}\right)^2} \quad \text{4-15}$$

$$\ln K_2 = \frac{7096.28}{T} + (-6.567) \ln T + \frac{7.466 \times 10^{-3} T}{2} + \frac{-2.164 \times 10^{-6} T^2}{6} + \frac{0.701 \times 10^{-5}}{2T^2} + 33.0 \quad \text{4-16}$$

The values of K_1 and K_2 can be determined using the Gibbs free energy provided by Equations 4-14 and 4-16 (Silva et al., 2019), (La Villetta et al., 2017); (Yan et al., 2018).

$$lnK = \frac{-\Delta G^0}{RT} \quad \text{4-17}$$

$$\Delta G^0 = \textstyle\sum_j n_j \; g^0_{f,T,i} \quad \text{4-18}$$

Where; n_j is the stoichiometric coefficients of the j products species; R is the universal gas constant; ΔG^0 is the standard Gibbs function of the reaction; $g^0_{f,T,j}$ is the standard Gibbs function of the formation of gas species *j*, at a specific temperature *T*, and it may be determined using the equation 4-19.

$$\Delta g^0_{f,T,j} = h^0_{i,j} - aTlnT - \mathrm{b}T^2 - \frac{c}{2} T^2 - \frac{d}{3} T^4 + \frac{e}{2T} + f + gT \quad \text{4-19}$$

The enthalpy of formation of the gases and the values of coefficients a - g are shown in Table A-1 of Appendix A.

4.3 Analysis of Energy Balance in the Reactor

The energy of a biomass gasifier is quantified by its heating value, the quantity of heat liberated when a specified unit of biomass is combusted. There are two heating values: low heating value and high heating value. The net or lower heating value is found by subtracting the latent heat of vaporization of water vapor created during combustion. The high or gross heating value is the amount of heat generated by the complete combustion of a given quantity of fuel. It is achieved when all the products of combustion are returned to the pre-combustion conditions, with the condensation of any water vapor that has been formed in the combustion process. (Silva et al., 2019).

The overall energy balances for biomass gasification in one Kmole of biomass fuel was wrote in the Equation 4-20 (La Villetta et al., 2017).

$$LHV_{biomass} + y_a \Delta h_a = y_g\left(\Delta h_g + LHV_g\right) \quad \text{4-20}$$

Where y_a is mole of air and y_g mole of gas in one Kmole and $\Delta h_a$and Δh_g is also change enthalpy of air and producer gas respectively.

$$\Delta h_a = y_{O_2} \int_{T_0}^{T_p} C_{p,O_2}\ dT + y_{N_2} \int_{T_0}^{T_p} C_{p,N_2}\ dT \quad \text{4-21}$$

Considering the simplification assumptions of an adiabatic process without external work and negligible variations of kinetic and potential energy, the Equation 4-22 is obtained;

$$\sum_j y_j\, h_{f,j}^0 = \sum_j y_j\ (h_{f,j}^0\ - \Delta h_T) \quad \text{4-22}$$

Regarding the terminology that defines the energy balance:

- y_i represents the total moles of gasification reactants used in the process that exist in the atmosphere;
- $h_{f,i}^0$ and $h_{f,j}^0$ are the enthalpy of reactant and product formation respectively;
- y_j represents the number of moles of the product species.
- $\Delta h_T = h(T) - h\ (T_0\ )$ is the sensible enthalpy of overall products gasification reaction in air present.

$h\ (T_0\ )$ is the enthalpy in kJ/kmol at the standard conditions (To = 25 ^{0}C, P = 1atm) and h (T) is the enthalpy in kJ/kmol at any state conditions.

$$\Delta h_g = \sum_j y_j\ (h_T - h(T_0\ )) = \sum_j y_j\ \int_{T_0}^{T} C_{pj} dT \quad \text{4-23}$$

Constant pressure specific heat of the gas values is given in Table A:2 in Appendix A. The enthalpy of formation of biomass in the reactants depends on the properties of the products formed (La Villetta et al., 2017). For the ideal gases considered in this model, the specific heat capacity at constant pressure is given by third-order polynomial expressions.

$$LHV_{fed} = HHV_{fed} - 9mHh_{fg} \qquad 4\text{-}24$$

Where; mH, h_{fg}, LHV and HHV are stand for mass fraction of hydrogen in the solid fuel, enthalpy of vaporization of water, and lower and higher heating values of biomass feedstock (MJ/kg), respectively. Utilizing the modified Dulong Formula for biomass, determine the HHV.

$$HHV = 0.349C + 1.178H + 0.10051S - 0.10381O - 0.0151N - 0.0211Ash \qquad 4\text{-}25$$

where C, H, O, N, and Ash represent the specific mass percentages of carbon, hydrogen, oxygen, nitrogen, and ash in the dry solid fuel, respectively. The lower heating value of syngas can be calculated by increasing the volume fraction x_j of the products of the gasification reaction, for the corresponding lower heating value LHV_j.

$$LHV_{gas} = \sum_j x_j \left(LHV_j\right) \qquad 4\text{-}26$$

Table 4:1 Standard heating values (Affam and Balegha, 2022).

Components	*LHV* (MJ/Nm^3)	*HHV* (MJ/Nm^3)
CH_4	35.88	39.82
CO_2	–	–
H_2	10.78	12.74
CO	12.64	12.63
N_2	–	–

4.4 The Exergy Analyses

An effective method for employing the second law of thermodynamics along with the conservation of mass and energy to the design and study of biomass conversion through gasification is energy analysis. The ratio of the effective exergy outputs from the gasifier to the required exergy input is known as the exergy efficiency (La Villetta et al., 2017). Exergy efficiency may not be commonly utilized; instead, the most commonly used are exergy efficiency and cold gas efficiency, which were previously discussed. Exergy can be separated into four different components: kinetic, potential, chemical, and physical, according to (Silva et al., 2019). Equation 4-27 shows that the exergy can be expressed as the total of the chemical and physical exergy, eliminating the kinetics and potential effects. Equation 4-29 presents the ideal gas mixture's chemical energy as the sum of the standard chemical exergies of its constituents less the work of compression, whereas Equation 4-27 presents the mixture's physical energy at any temperature and pressure.

$$Ex, \text{total} = Ex_{chem} + Ex_{phy} \tag{4-27}$$

$$\eta_{ex} = \frac{Ex_{syngas}}{Ex_{biomass} + Ex_{gas}} \tag{4-28}$$

where,

- η_{ex} is the efficiency of exergy system;
- Ex_{phy} is physical exergy of gas produced;
- Ex_{fuel} is exergy of feedstock;
- Ex_{gas} is the exergy of the gasifying medium;

4.4.1 Chemical Exergy of Gas

The chemical exergy of the product gas stream consisting of various components are expressed as a function of its individual components and their respective molar fractions. This is calculated using the weighted sum of the chemical exergies of the components, reflecting their contributions to the total exergy (Osei et al., 2023).

$$Ex_{ch,gas} = \sum_j x_j \left(Ex_{ch,j}\right) + R_0 T_0 \sum_j x_j \left(ln x_j\right) \tag{4-29}$$

where, $Ex_{ch,gas}$ is chemical exergy of producer gas; x_j is the fraction of molecular exergy of each particular gas component j, $Ex_{ch,j}$ represented chemical exergy of different gas components j, R_0 is the universal constant for gases (8.314 kJ/kmolK), T_0 is the standard temperature (25 ^{0}C) shown in Table 4:2.

Table 4:2 Standard species chemical exergy(Yan et al., 2018)

Species	$Ex_{ch,j}$ (kJ/kmol)
$H_2O(g)$	11710
CO_2	20140
H_2	238490
CH_4	836510
CO	275430
N_2	720

The value of x_j for any components can be determined by dividing the number of molecules of any gas component, y_j , (CO, CO_2, H_2, H_2O, CH_4, N_2) by the total number of molecules of all of the gas components, $\sum y_j$, under specific conditions, as expressed in the Equation 4-30.

$$x_j = \frac{y_j}{\sum y_j} \qquad 4\text{-}30$$

$$\sum x_j = 1 \qquad 4\text{-}31$$

4.4.2 The Physical Exergy of Gas

The amount of physical exergy in the ultimate gas is significant since the process of gasification was designed to exist at higher temperature of gasification.

$$E_{phy} = (h_R - h_o) - T_0\,(S_R - S_o) \qquad 4\text{-}32$$

where,

- E_{phy} is physical exergy of gas produced
- h_R is enthalpy of exist gas at standard state from the gasifier
- h_o is Molar specific enthalpy at original state of the environment
- T_0 is standard temperature at 25 ^0C
- S_R is entropy of exist gas at standard sate from the gasifier
- S_o is the original condition of the environment's molar specific entropy;

Reduced tar content in the produced gas, efficient heat transfer, and a faster biomass conversion process is the intended effects of using highly preheated air.

$$\mathrm{E_{phy}} = \int_{T_0}^{T} \sum_j x_j \overline{c_{p,j}}(\mathrm{T})\ dT - T_0 \left(\int_{T_0}^{T} \frac{\sum_j x_j \overline{c_{p,j}}(T)}{T}\ dT - R \sum_j x_j \ln x_j \right) \qquad 4\text{-}33$$

$$E_{gasif} = (h_H - h_o) - T_0\,(S_H - S_o) \qquad 4\text{-}34$$

where, E_{gasif} is preheated air exergy of the gasifying medium, h_H is a given temperature's enthalpy of the gas mixture, S_H represents the gas mixture's entropy at a specific temperature, h_o enthalpy and S_o is values of entropy in the original state at standard temperature T_0 (25 ^0C) and pressure (1 atm).

4.4.3 Chemical Exergy of Biomass

Exergy is the gasification air enter the updraft gasifier at the standard state reference condition was determined with molar analysis of 21% oxygen and 79% nitrogen and only involves the chemical exergy part, as the physical exergy becomes zero in the dead state (h = *ho* = 0 and S= *So*). For the exergy of moisture content H_2O, the chemical part is considered only; because it was assumed biomass fuel enters gasifier at the original state (Eliraison Moshi et al., 2019).

$$E_{biomass} = \gamma LHV_{biomass} \quad 4\text{-}35$$

$$\gamma = \frac{1.0414 + 0.0177\left(\frac{H}{C}\right) - 0.3328\ 1 + 0.054\left(\frac{H}{C}\right) + 0.0493\left(\frac{H}{C}\right)\left(\frac{N}{C}\right)}{1 - 0.4021\left(\frac{O}{C}\right)} \quad 4\text{-}36$$

Where, C, O, H and N are of Carbon, oxygen, Hydrogen and Nitrogen, weight fraction respectively in the biomass ultimate analysis and γ is represent the ratio of chemical exergy and the LHV of the biomass.

4.4.4 Cold Exergy Efficiency

The desirable that the energy that could be converted into work but wasted (irreversibility, I) should be as small as possible it to have high system efficiency.

$$I = (1 - \eta_{ex,chem}) \quad 4\text{-}37$$

where, $\eta_{ex,chem}$ is the efficiency of chemical exergy in the process

$$\eta_{ex,chem} = \frac{\eta_{gas}(E_{chem,gas} + E_{phy,gas})}{E_{chem,biomas}} \quad 4\text{-}38$$

$$\eta_{gas} = \frac{LHV_{gas} * Q_{gas}}{LHV_{biomass} * m_f} \quad 4\text{-}39$$

where; η_{gas} is efficiency of gasification Q_{gas} is volume gas flow rate (*m^3 /s*) m_f is mass of biomass fuel consumption (*Kg/s*) LHV_{gas} and $LHV_{biomass}$ are Lower Heating Value of gas (*KJ/Nm^3*) and LHV of biomass (*KJ/kg*) respectively (Eliraison Moshi et al., 2019). In this research, the low heating values for biomass and product gas for each syngas component obtained from the corn and wheat straw were evaluated.

4.5 Analytical Measurements of Biomass

4.5.1 Physical Parameters

The total amount of water that makes up a biomass sample's mass is defined as moisture. It is an essential parameter that influences the physical properties of biomass.

4.5.2 Chemical Parameters

The compositions of element that compos biomass (C, H, O and N). The ash contents (inorganic element) and behaviour were interested.

4.5.2.1 Elemental Analysis

Through elemental analysis, researchers can determine the mass of element that are most abundance in the molecular compositions of organic material; carbon (C), hydrogen (H), nitrogen (N), oxygen (O) and sulphur (S) (Lei et al., 2023).

Table 4:3 Ultimate analysis Corn cobs biomass samples (% Weight) (M. A. Sulaiman et al., 2019), (Lei et al., 2023)

Biomass type	% C	% H	% O	% N	% S	HHV (MJ/kg)
Corn Cobs	48.56	6.22	44.2	0.64	0.03	17.2 MJ/kg
Wheat straw	45	5.8	48.84	0.3	0.06	17.65 MJ/kg

For combustion, precise air (stoichiometric air), for instance, may be ascertained by establishing the oxidation reactions on the basis of the knowledge of these constituents. In addition, there are certain empirical formulations that enable us to approximate each element’s energy content (calorific value) depending on its percentage by weight.

4.5.3 Proximate Analysis

The biomass's moisture content, volatile matter, ash, and fixed carbon content are all determined by proximate analysis and are given as percentages by weight. The main purpose of this analysis is to determine which portion of the biomass preserves its inert fraction (ash and moisture) and chemical energy (fixed carbon and volatile chemicals). The part of fuel that is emitted as gases and vapors (hydrocarbons) during the thermal breakdown of biomass is known as volatile matter. The fractions left over after the volatile substance has been expelled are ashes and fixed carbon. After the release of volatiles, fixed carbon in combustion processes continues to burn slowly. From Figure A.5 of Appendix contain information is illustrate in Table 4:4, proximate analysis of samples. This analysis was for biomass samples were selected for used as feedstock for this study was conducted, in Geochemical Laboratory Desk at Geological Institute of Ethiopia find in Addis Ababa, Ethiopia.

Table 4:4 Proximate analysis Corn cobs and Wheat stalk biomass samples (% Weight)

Biomasses	Moisture %	Volatile%	Ash%	Fixed Carbon%	HHV (MJ/kg)
Corn Cobs	6.18	76.85	3.99	12.97	16.73 MJ/kg
Wheat straw	6.03	73.24	9.89	10.85	13.7033 MJ/kg

4.5.4 Energy Parameter

The amount of chemical energy in a fuel that may be directly converted into thermal energy through thermochemical combustion, can be described as its calorific value. Energy per mass units, often kJ/kg or MJ/kg, are used to express this property (Z. Wang & Baniotopoulos, 2023).

4.6 Design Considerations and Specifications of Throated Updraft Gasifier

Any biomass gasification system design should be considered the gasifier's specifications and intended use. The input consists of the fuel specifications, the gasification medium, and the intended product gas composition.

4.6.1 Design of the Gasifier

The use of empirical relations, some experimental data, and computations are used in the design process. The size of the gasifier reactor was as follows:

- Both the gasifying agent and the gasifier’s capacity (thermal power output) were fixed;
- The right gasifier sizing parameter was identified using mathematical formulas and experimental data.
- The type of biomass, the efficiency of the gasifier, and the syngas lower heating value (LHV) were selected.

For the throat updraft gasifier design, these parameters are appropriate: throat diameter, biomass type, equivalency ratio, air tuyere diameter, specific rate of gasification, relative reactor tube capacity, reactor hopper diameter, reactor hopper height, throat height, reduction zone height, and reactor hopper height.

4.6.1.1 Fuel Consumption Rate (FCR)

Fuel consumption rate is a vital metric in the gasification process, particularly for biomass gasification. FCR measured the quantity of biomass consumed relative to the power generated while gasification process (Yan et al., 2018).

$$FCR = \frac{P_{\text{out}}}{HHV \times \eta_{\text{gasification}}} \qquad 4\text{-}40$$

where; P_{out} is Thermal power output and *HHV* is high heating values of biomass.

4.6.1.2 The rate of fuel feed

The rate of fuel fed in gasification is measured the quantity of biomass is feed into gasifier as per unit of time which determined by mass. It significantly affected in determined the gasification efficiency, quality of syngas production, and the thermal performance of the gasification process (Suhartono et al., 2020); (Saputro et al., 2018).

$$m_f = \frac{P_{\text{out}}}{LHV_{\text{biomass}} \times \eta_{\text{gasification}}} \quad \text{4-41}$$

4.6.1.3 Air Flow Rate (AFR)

In the gasification process the flow rate of air is an important parameter that affected the quality and efficiency of producer gas. This study illustrated that the selected AFR may be improved the conversions of biomass feedstock promoting better combustion and decreased tar formation in reactor (Akhator et al., 2019; Saputro et al., 2018).

$$\frac{m_a}{m_f} = 2.6667 * C + 8 * H - O \quad \text{4-42}$$

where; m_a is the air mass needed for completed combustion and m_f is corn cob mass that utilized for ignition. The C, H and O are represented the weight percent of carbon, hydrogen, and oxygen in fuel respectively. Oxygen constitutes 23% of air's weight; thus, in 1 kg of oxygen, there is 4.3478 kg of air (calculated as 100/23). Therefore, Equation 4-43 can be utilized to determine the less amount of air needed for completed combustion of 1Kg of fuel.

$$(A:F)_{stoich} = 4.3478 * \frac{m_a}{m_f} \quad \text{4-43}$$

Where; $(A:F)_{stoich}$ is stoichiometric of air flow ratio; for one kilogram of fuel, the actual air-fuel ratio (A: F) at the expected equivalency ratio can be expressed using Equation 4-44.

$$\text{AFR} = \left(\frac{m_a}{m_f}\right)_{\text{actual}} = ER * (A:F)_{stoich} \quad \text{4-44}$$

4.6.1.4 Produced Gas Flow Rate (Q_g)

The volume flow rate of product gas, denoted as Q_g, represents the volume of gas flowing through a given cross-sectional area per unit time. It is typically expressed in units such as cubic meters per second (Nm^3/hr) (Saputro et al., 2018); (Vnuchkov et al., 2022).

$$Q_g = \frac{P_{\text{out}}}{LHV_{\text{gas}}} \quad \text{4-45}$$

4.6.1.5 Specific Gasification Rate (SGR)

The specific gasification rate (SGR) is a crucial parameter in the operation of gasifiers, particularly in determining efficiencies and performance of gasification processes (Vnuchkov et al., 2022).

$$SGR = \frac{Q_g}{A_{\text{throat}}} \qquad \text{4-46}$$

where; A_{throat} is area of the throat of the gasifier (m^2).

4.6.1.6 Throat Design

In updraft gasification, air is drawn in from the bottom of reactor while the feedstock is supplied at the top of reactor (Vyas et al., 2021). The throat diameter of gasifier which determined by the Specific Gasification Rate (SGR) value (Akhator et al., 2019). Hence,

$$A_{\text{throat}} = \frac{Q_g}{\text{SGR}} \qquad \text{4-47}$$

$$A_{\text{throat}} = \pi * d_{\text{throat}} * \pi * h_{\text{throat}} \qquad \text{4-48}$$

$$d_{\text{throat}} = \frac{A_{\text{throat}}}{h_{\text{throat}} * \pi} \qquad \text{4-49}$$

The ratio of throated height to diameter of throated is equal to 1.5 for the stability of biomass flow inside the gasifier (Akhator et al., 2019).

$$h_{\text{throat}} = 1.5 \times d_{\text{throat}} \qquad \text{4-50}$$

4.6.1.7 Reduction Zone Height

Throat diameter of an updraft gasifier affected by height of the reduction zone in order to ensure gasification efficiency (Akhator et al., 2019).

$$h_{\text{reduction}} = 2.5 \times d_{\text{throat}} \qquad \text{4-51}$$

4.6.1.8 Diameter of Rector Hoppe

The diameter hopper is crucial for efficient biomass feeding and gasification in throat updraft gasifiers (Moshi et al., 2020).

$$A_{\text{hopper}} = \pi * d_{\text{hopper}} * h_{\text{hopper}} \qquad \text{4-52}$$

where; A_{hopper} is area of hopper. The diameter of the hopper reactor can be derived from Equation **Error! Reference source not found.**;

$$d_{\text{hopper}} = \frac{A_{\text{hopper}}}{\pi * h_{\text{hopper}}} \quad \text{4-53}$$

4.6.1.9 Diameter of the Tuyere

Tuyer is the location of the reactor's air inlet. Several tuyeres positioned around the reactor's perimeter provide a consistent distribution of air to the reaction zone. The tuyere's area is determined by dividing its total number through the air supply's entire cross-sectional area.

$$d_{\text{tuyer}} = 1.27 \times \sqrt{\text{AFR} \times v \times n} \quad \text{4-54}$$

where; d_{tuyer} is the tuyere, *v* is velocity of air entering the tuyeres (in *m/s*), *n* is numbers of tuyeres, and *AFR* is air fuel ratio (m_a/m_f).

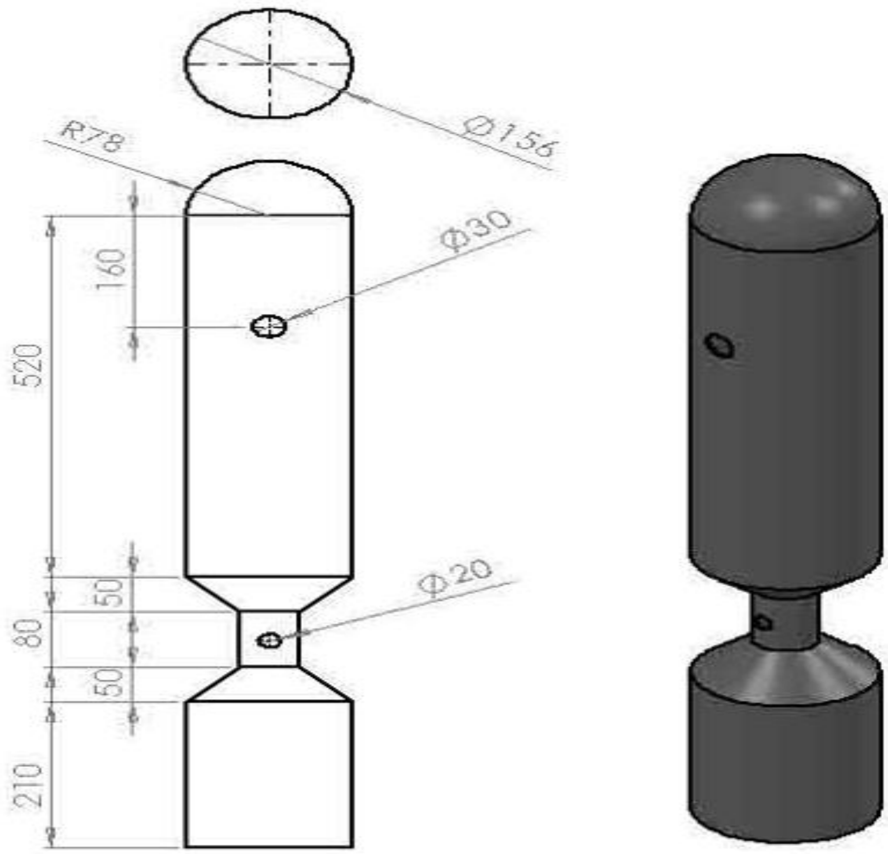

Figure 4.1 Gasifier reactor zone with throat design

4.6.1.10 Grate in Gasifier

A grate in the gasifier separates the biomass that is going through gasification from waste materials like char and ash, which are gathered in the ash pit at the gasifier's base. Grate have gaps between the grate element to allow ash and char to pass through while retaining most of biomass.

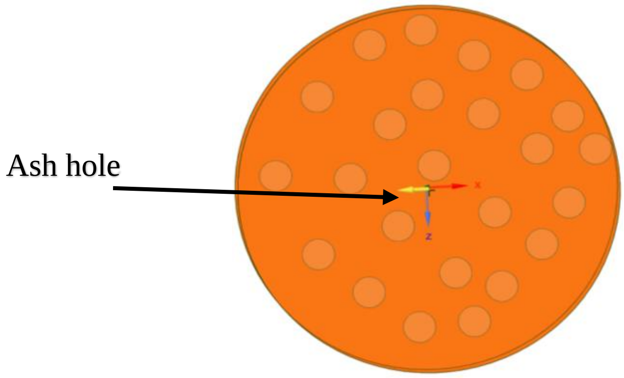

Figure 4.2 Schematics of grate gasifier design

4.6.2 Design of Cyclone Separator

The gas cyclone separator is device that allows gas to enter a cylindrical tangentially. The height and cone section are related to cylinder diameter in order to characterize cyclone separator design (Bhardwaj et al., 2019)

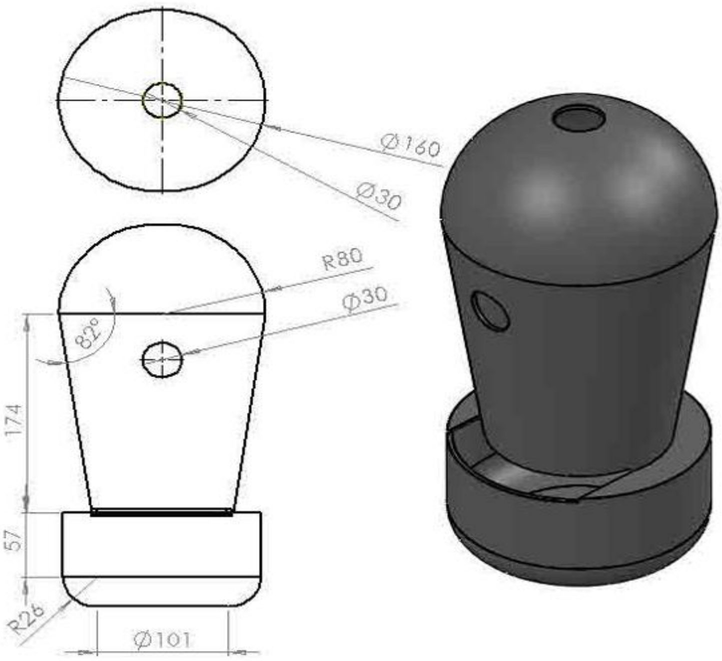

Figure 4.3 Cyclone separator of throat updraft gasifier

4.7 Analysis Chemical Formula of Corn Cob and Wheat Straw

The final analysis from Table 4:3 was used to calculate the chemical formula for maize cob and wheat straw. As shown in Tables 4:6 and 4:7, the chemical formula of wheat straw and corn cob can be calculated as follows. The molar mass was calculated by dividing each weight percentage by the molecular mass of atoms using the weight percentages that were acquired during final elemental analysis. It is crucial to divide the carbon and obtain the values of (x, y, z) in order to make the calculation of the stoichiometric chemical formula more convenient.

Table 4:5 Chemical formula of corn cob calculation

Species	Molar mass	Weight%	$\frac{Weight\%}{Molar\ mass}$	Divided to Carbon	Values of (x, y, z)
C	12.011	48.56	4.042961	$^{4.042961}/_{4.042961}$	1
H	1.008	6.22	6.170635	$^{6.170635}/_{4.042961}$	1.526266
O	15.999	44.2	2.6376649	$^{2.6376649}/_{4.042961}$	0.65241
N	14.007	0.64	0.0457143	$^{0.045714}/_{4.042961}$	0.011307

Table 4:6 Chemical formula of wheat straw calculation

Species	Molar mass	Weight%	$\frac{Weight\%}{Molar\ mass}$	Divided to Carbon	Values of (x, y, z)
C	12.011	45	3.7465656	$^{3.7465656}/_{3.7465656}$	1
H	1.008	5.8	5.78397	$^{5.78397}/_{3.7465656}$	1.543806
O	15.999	48.84	3.05269	$^{3.05269}/_{3.7465656}$	0.814798
N	14.007	0.3	0.02143	$^{0.02143}/_{3.7465656}$	0.0057209

The chemical formulas of corn cob and wheat straw, $CH_xO_yN_z$, were determined based on Tables 4:6 and 4:7, the calculated values were as written as $CH_{1.526266}O_{0.65241}N_{0.011307}$ and $CH_{1.543806}O_{0.814798}N_{0.0057209}$ respectively.

4.8 Summary of Design Considerations and Numerical Analysis of Gasifier

Table 4:7 Summary of Gasifier design parameter equation and calculation analysis

Name of parameters	Symbol	Equation no.	Values	Unit
Fuel Consumption Rate	FCR	4-40	1.1578	$\frac{Kg}{h}$
Small amount of oxygen to biomass	$\frac{m_a}{m_f}$	4-42	1.343	$\frac{Kg\ of\ oxygen}{Kg\ of\ biomass}$
Stoichiometric of air flow ratio	$(A:F)_{stoich}$	4-42	5.839	$\frac{Kg\ of\ air}{Kg\ of\ biomass}$
Air flow rate	AFR	4-44	1.5	$\frac{Kg\ of\ air}{Kg\ of\ biomass}$
Produced gas flow rate	Q_g	4-45	4.95	m^3/hr
Area of throat	A_{throat}	4-47	0.0134	m^2
Diameter of throat	d_{throat}	4-49	0.0533	m
Height of throat	h_{throat}	4-50	0.08	m
Height of reduction	$h_{reduction}$	4-51	0.133	m
Area of hopper	A_{hopper}	4-52	0.255	m^2
Diameter of hopper	d_{hopper}	4-53	0.156	m

CHAPTER FIVE

EXPERIMENTAL SETUP AND PROCEDURE

5.1 Over View

In this chapter, the experimental set up of throat updraft gasifier have discussed. The materials used for constructing parts of the gasifier, measuring devices such as digital thermometer and gas analyser are going to be discussed in great detail. The development process of main parts of gasifier together with the assemble of the overall experimental setup carried with images of another auxiliary device was also presented.

5.2 Fabrication Process

The manufacturing process of the throated updraft gasifier involved sourcing its components from the local market, with careful consideration given to the cost and available of materials. The selection process prioritized affordability and ease of access to ensure practically for production. The materials chosen include high strength metal and heat resistant components to with stand the high temperature involves in the gasification process. The dimension of each parts was determined based on the theoretical analysis, as detailed in Section 4.6 of design analysis. This section provided necessary specification to ensure that all components were manufactured to the exact measurements required for efficient syngas production.

5.2.1 Gasifier Reactor with Throat

The throat updraft gasifier reactor was constructed by rolling and welding a metal sheet in to a cylindrical shape with circular plates welded at the top open and bottom closed. In the reactor, distinct functional zone was incorporated including the pyrolysis zone where biomass underwent thermal decomposition to release volatile gases and combustion zone where partial oxidation occurred to generated the necessary heat for gasification. A grate was installed at the bottom to support the biomass while allowing ash to fall through, maintaining efficient operation. Additionally, a tuyere was integrated into the reactor to facilitated controlled airflow, ensuring proper combustion and gas flow dynamics.

Figure 5.1 Fabricated different reaction zone of throat updraft gasifier

5.2.3 Cyclone separator of Gasifier

The cyclone separator illustrated in Figure 5.2, is manufactured from mild steel, ensuring durability and resistance to high temperatures in the gasification process.

Figure 5.2 Manufactured cyclone separator for gasifier

It operates by utilizing centrifugal force to separate solid particulates such as char, ash, and tar from the producer gas. The conical shape enhances particle separation efficiency, while the welded joints provide structural strength. Mild steel was chosen for its cost-effectiveness, ease of fabrication, and sufficient thermal resistance in gasification applications.

5.2.2 Stand of Gasifier

The gasifier holder shown in Figure 5.3 was fabricated from mild steel hollow rectangular bars, ensuring a strong and stable support structure. It is designed to withstand the weight of the gasifier and associated components while maintaining durability. The rectangular bar construction provides rigidity and resistance to deformation under operational conditions.

Figure 5.3 Fabricated stand of gasifier

5.2.3 Description of the thermocouples that used

Thermocouple were installed on the gasifier for read temperature distribution. The K-type thermocouple are robust and reported to have a measurement range 0 to 1050 ^{0}C. Thus K-type thermocouple were used to keep a check gasifier's internal function.

Seven thermocouples are used to measure the gasifier temperature for the purpose of thermal analysis as shown in Table 5:1. Thermocouple were installed on exhaust gas line at two placed and five placed on reactor to read the thermal property of the syngas exiting from gasifier.

Table 5:1 Thermocouple location on diffirent gasifier

Parts	Numbers of port	Symbol
Ash pit zone	1	T_1
Reduction zone	1	T_2
Oxidation zone	1	T_3
Pyrolysis zone	1	T_4
Dry zone	1	T_5
Temperature exit from reactor	1	T_6
Temperature exit from cyclone separator	1	T_7

5.3 Biomass Preparation

Preparing and pre-treating biomass feedstock for gasification requires several of important steps that improve its performance, as shown in Figure 5.4.

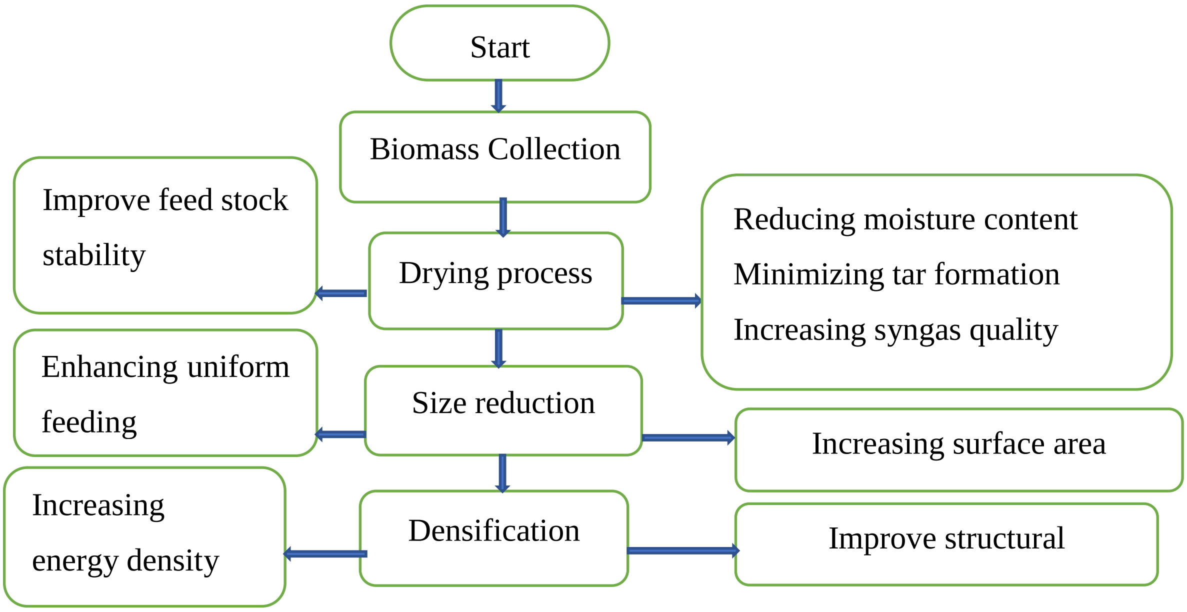

Figure 5.4 Preparing and pre-treating of biomass for experimental process

It first with collections of corn cob and wheat straw around Adama area, and washed by distilled water to remove unwanted particles from samples, then after dried by sun for three days. Once the biomass is ready, it undergoes sample grinder. This step is crucial as it reduces the materials into smaller, uniform particles, increasing surface area for better combustion and improving efficiency in subsequent process. After grinding the sample is subjected to sample sieving which a sieve is used to separated samples based on their size. This ensure uniformity, which is essential for achieving consistent results in gasification. After the sieving the sample drying step process where the ground material is placed in an oven to remove moisture. This process is important because high moisture content can reduce exergy efficiency and effected the quality of syngas production during gasification. As shown in Figure 5.5 the process preparing wheat straw and corn cob biomass involves very important steps to ensuring consistency and suitable for gasification.

Once adequate dried the sample is then processed through sample pelletizing, where the fine particles of corn cob and wheat straw are compressed into dense pellets using a hydraulic press pelletizing machine. Pelletizing enhance the material's handling and storage while also improving its energy density, making it more efficient for gasification.

Figure 5.5 Feedstock sample preparation

5.4 Measuring Devices that Used for Parameters Determination

Several important instrumentations illustrated in Figure 5.6; measures are required during the gasification process to produce syngas in order to ensure system control, accuracy, and efficiency. The thermometer and thermocouple are used to measure ambient and medium distributive temperatures in the gasifier respectively, ensuring that the necessary thermal conditions for pyrolysis, combustion, and reduction reactions are met. High temperatures are essential for breaking down the feedstock into syngas, and these temperature readings help optimize the process. The exhaust gas analyser detects the quantities of gases such carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4). The anemometer measures the airflow rate inside the gasifier, which is crucial for controlling the oxygen supply and ensuring proper combustion and gasification reactions. In the gasification process, the preparation of the feedstock is also crucial and calls for exact measurements and processing methods. The biomass's surface area is increased for increased gasification efficiency by using the coffee grinder to reduce the biomass's particle size. An oven is subsequently used to dry the prepared sample in order to lower its moisture level, since too much moisture can hinder the generation of syngas. A sieve is used to achieve uniform particle sizes, which helps maintain a consistent reaction environment. These instrumentation tools and techniques collectively contribute to the efficient production of syngas by improved the gasification process parameters.

Figure 5.6 Instrumental devices used for different parameters

5.5 Experimental Procedure for Gasification

Biomass gasification process in a throated updraft gasifier begins with the preparation and loading of feedstock, as corn cob and wheat straw, into the reactor. The gasifier is then ignited at the grate level, initiating the drying, pyrolysis, oxidation, and reduction, zones as the biomass moves downward. An anemometer is installed at the air inlet to gauge the speed of the incoming air, allowing for airflow monitoring and assurance of suitable gasification conditions. Thermocouples are used to measure the temperature in different areas of the reactor, allowing for thermal gradient tracking and combustion improvement. As gasification progresses, the producer gas exits through the top of the gasifier and is analysed for quality. An exhaust gas analyser is used to measure the concentrations of CO, CO_2, and CH_4 proved the syngas composition. The collected instrumental data is continuously monitored and recorded to assess gasification performance and make necessary adjustments for improved process.

5.6 Experimental Setup of Gasifier

To start the experimental analysis a sample of grinded biomass such as corn cob and wheat straw was placed into the throated updraft gasifier. Some amount of biomass was feed to compensate the low air fuel rate from the compressor. Ignition was initiated through the ignition port and let opened until the compressor starts supplying the compressed air. After the combustion of feedstock, and gasifying air was started, the fan was turned on for 5 minutes, before starting to measure the syngas on Gas analyser. This was done because Syngas approaches the test port few moments later after the gasification was began. A 1.5 kg of feedstock for each combustion and one samples for three time with different pellet size. The air from the compressor minimized to manage the fuel to air ratio required. A Fan was used to facilitate the flow of syngas out of cyclone rapidly as much as possible and to enable uniformly varying precise reading of Syngas at the test port. It was operated by connecting it to direct power source.

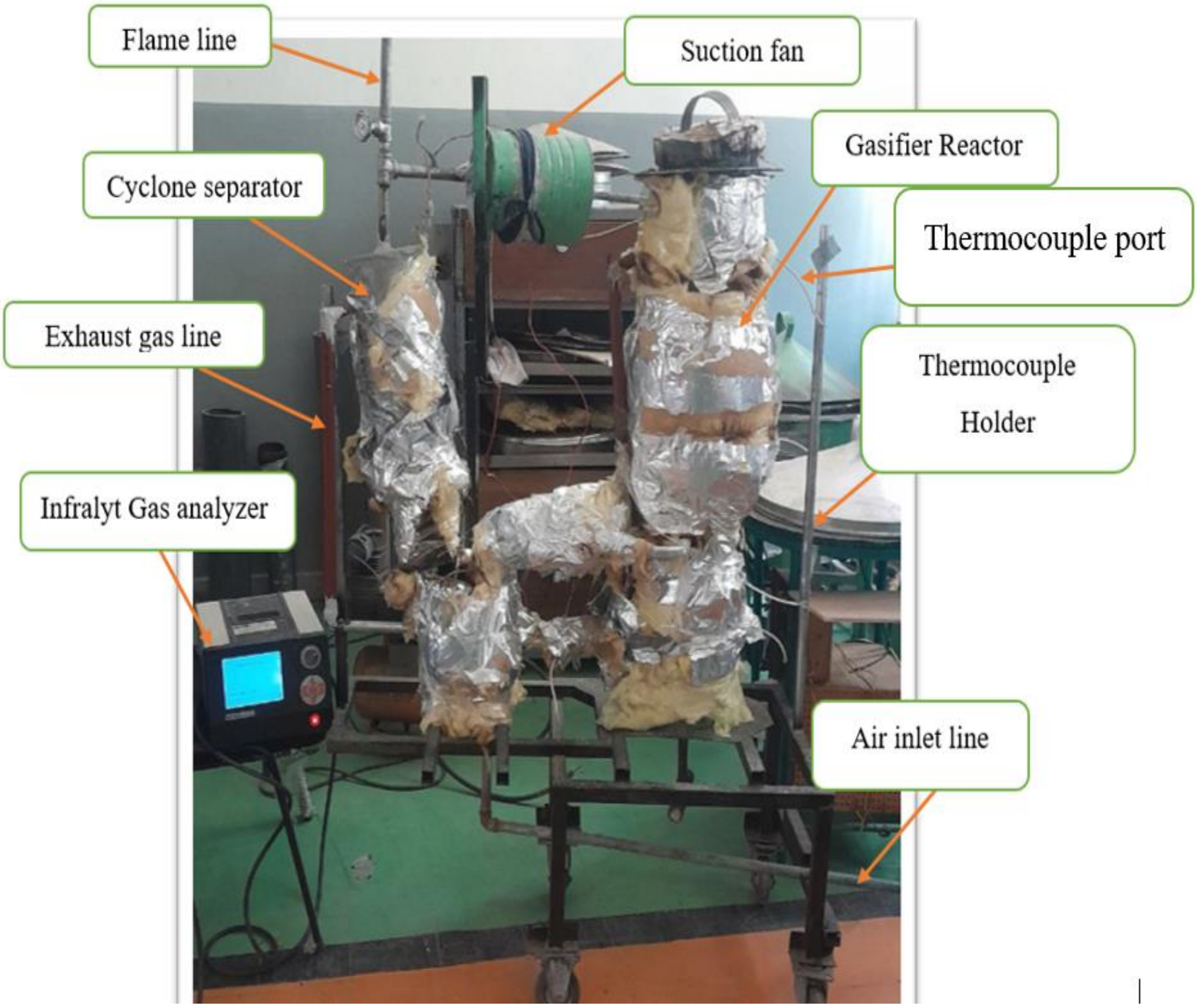

Figure 5.7 Throat updraft gasifier Experimental Setup

CHAPTER SIX

RESULT AND DESCUSION

6.1 Over View

In this chapter, the theoretical and experimental results obtained from the designed throat updraft gasifier are presented. The shown equilibrium results are compared with data from experiments and previous research in order to verify and validate the theoretical analysis.

6.2 Thermodynamic Equilibrium Model Analysis

The thermodynamic equilibrium model (TEM) was studied the gasification process in a throat updraft gasifier, were utilizing corn cob and wheat straw as feedstock. The model was validated for accuracy before the analysis was the studied then investigated the effect of MC, ER, and GT on the composition of producer gas, lower heating value, and exergy efficiency. Sensitivity analysis was carried out by adjusting one parameter at a time while keeping the others constant. The default values for these parameters were based on experimental data. For the simulations, two types of biomass were used. The first was corn cob, with an elemental composition of 48.65% carbon, 6.22% hydrogen, 44.10% oxygen, 0.51% nitrogen, and 0.01% sulphur, and an HHV 16.73MJ/Kg. The other biomass feedstock was wheat straw which has 45.98% carbon, 6.48% hydrogen, 42.85% oxygen, 0.53% nitrogen and 0.02% sulphur and its LHV is 13.70 MJ/Kg. These compositions were determined on a dry ash-free basis, while proximate analysis provided information on moisture content, volatile matter, fixed carbon and ash content. This data helped define the feedstock composition, which was then used in the equilibrium model. The TEM calculations was employed the MATLAB tool. The model assumes the gasifier functions under an adiabatic condition. This simplifies the calculation and concentrating on estimating the equilibrium composition of syngas, including key components such as hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), and nitrogen (N_2).

6.2.1 Effect of Moisture Content

MC in biomass significantly influence the gasification process by influencing the energy needed for drying and pyrolysis. Higher moisture levels decreasing the efficiency of gasifier, which also reduced quality of syngas and raised tar formation.

6.2.1.1 Factor effect of MC on compositions of producer gas

Increasing moisture content in biomass feedstock between 5% to 25% for significantly affects the during gasification, lead to various compositions of producer gas results. Moisture content in the corn cob and wheat straw introduces additional steam into the reactor, which enhances exothermic reactions in Equation 4-10 and endothermic reaction in the Equation 4-12. These reactions lead to an increase in hydrogen (H_2) production, which is vital for applications requiring a hydrogen-rich gas

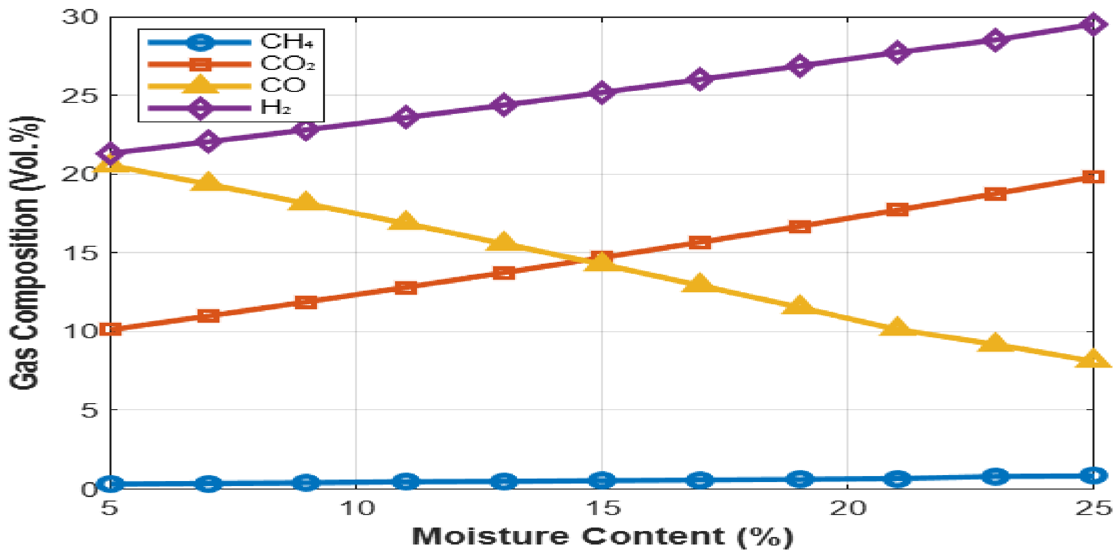

Figure 6.1 Factor affecting of moisture content on Compositions of producer gas for corn cob

However, the same reactions consume carbon monoxide (CO), decrease in its concentration. Increase the content of moisture in feedstock rise concentrations of CO_2 due the water shift reaction. Through methanation reaction CH_4 was formed can be experienced slight increase with moisture content; but this is often limit by operate temperatures and reaction kinetics. Therefore, higher moisture content improved H_2 yield, it also decreases CO and rise amount of CO_2 that affect the value of caloric and syngas quality (Kumar et al., 2016).

Decreasing CO with increasing MC is primarily due to water gas shift reaction where CO combined with H_2O(g) produce CO_2 and H_2. As MC is rise H_2O(g) is more available promoting in reaction Equation 4-12 and thereby decreasing the content of CO concentration while increase the amount of H_2 and CO_2. Additionally, higher MC can influence gasification temperature and reaction pathway within gasification process.

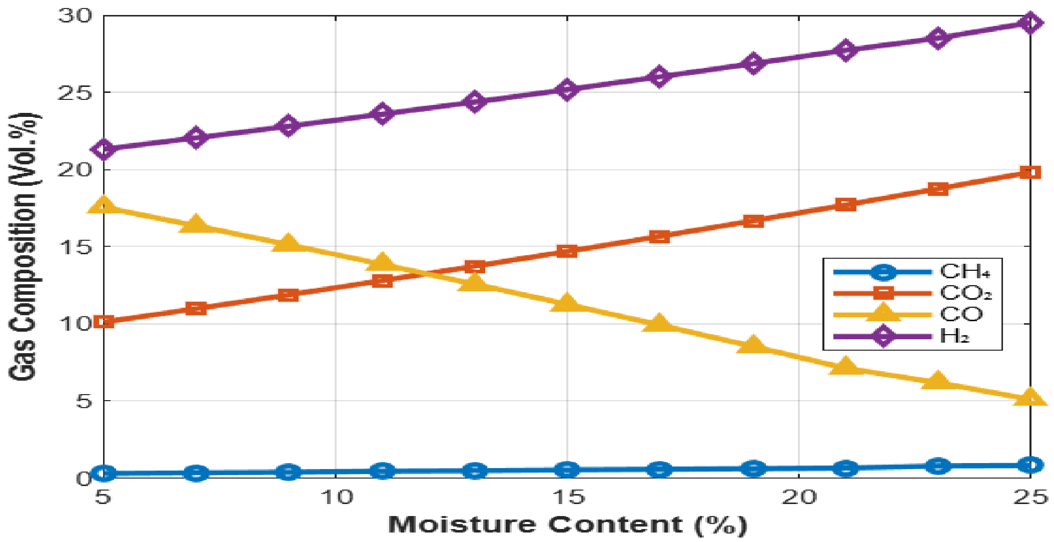

Figure 6.2 Factor affecting of moisture content on Compositions of producer gas for wheat straw

6.2.1.2 Summary of Moisture Content affecting on Syngas Composition

The Table 6.1 illustrates the variation in compositions of syngas with moisture content for two different biomass feedstocks; wheat straw and corn cob, CH_4, CO_2, CO, and H_2**.** As moisture content raise from 5% to 25%, at CH_4, CO_2, and H_2 compositions increase, while CO composition decrease for both feedstocks. In comparison, corn cob has higher CO and H_2 content, while wheat straw produces more CO_2 across the moisture range. CH_4 remains minor component, its concentration still gradually increases with moisture content.

Table 6:1 Effect of moisture content on producer gas

Producer Gas	Increasing MC (5%-25%)	Corn cob	Wheat Straw
CH_4	Increases	0.08 to 0.53	0.07 to 0.63
CO_2	Increases	10.12 to 18.55	10.49 to 18.72
CO	Decreases	21.56 to 9.60	18.47 to 6.29
H_2	Increases	21.63 to 29.34	21.03 to 28.81

These patterns summarized in Table 6:1 the influence of feedstock type and moisture content on producer gas.

6.2.1.3 Effect of Moisture Content on LHV of the syngas

Moisture content (MC) in biomass a crucial role in determined the LHV of producer gas, as it directly affected the energy balance and reaction mechanisms during gasification. Higher MC leads to raised water vapor in the gasifier, which enhanced steam reforming and water-gas shift reactions, promoted hydrogen (H_2) production. However, excessive moisture contents absorb a significant amount of the reaction heat, decreasing the overall gasification temperature. The reduced temperature limits the decompositions of complex hydrocarbons, resulting in higher CO_2 and lower CO concentrations, which negatively affected the syngas quality and decreased its LHV. The range of LHV of corn cob and wheat straw range 5.15 to 4.32NJ/Nm^3 and 4.85 to 3.94 MJ/Nm^3 when the range of moisture content 5% to 25%.

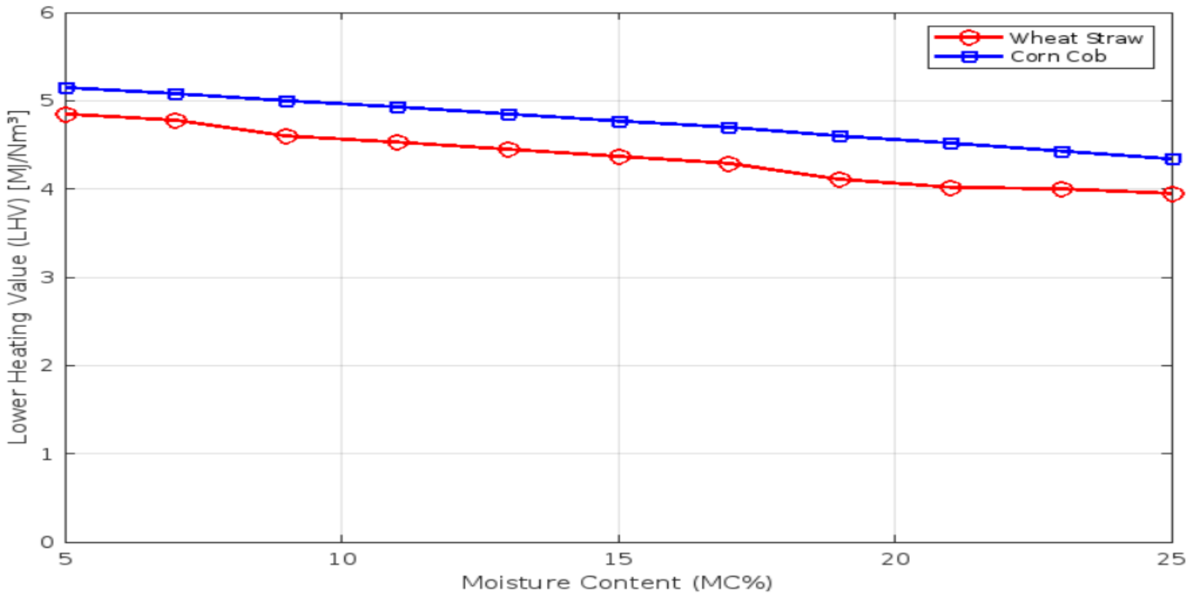

Figure 6.3 Factor affecting of moisture content on Lower heating values for corn cob and wheat straw

Additionally, a higher MC rises the latent heat required for water evaporation, diverting energy from gasification reactions and further lowering the energy content of the produced syngas. Conversely, when the amount of MC is decreased, the gasification process becomes more thermal efficiency, as low energy is used in evaporating moisture, allowing higher reaction temperatures. This results to rise the production of CO, which is vital for a higher LHV of syngas. In addition, lower moisture content reduced the water gas shift reaction in Equation 4-12, limited the conversion of CO to CO_2 and H_2, thereby preserving the combustible gas fractions. As a result, an optimal MC must be maintained to balances hydrogen production and minimizes energy losses, ensuring an efficient gasification process with syngas composition that supports a higher LHV.

6.2.2 Effect of Gasifying Temperatures

Gasification temperature significantly influences syngas composition and its lower heating value (LHV) by affecting the reaction rates and equilibrium of key gasification reactions. Higher temperatures generally enhance the production of CO and H_2 while reducing CO_2 and CH_4 concentrations, leading to improved syngas quality. Additionally, an increase in gasification temperature promotes endothermic reactions, boosting the overall energy content of the syngas and resulting in a higher LHV.

6.2.2.1 Effect of Gasifying Temperature on Syngas composition

Gasification temperature plays a crucial role in determining both the quantity and quality of syngas produced. As the temperature rises, biomass breaks down more efficiently, leading to higher yields of carbon monoxide (CO) and hydrogen (H_2), which are the key combustible components of syngas. This happens because higher temperatures accelerate reactions in Equation 4-9 (which converts carbon and carbon dioxide into more CO) and the water-gas reaction (which converts carbon and steam into CO and H_2). Additionally, increased heat helps crack heavier hydrocarbons and tars, producing a cleaner syngas with a higher energy content. However, if the temperature becomes too high, excessive oxidation can occur, leading to the formation of more carbon dioxide (CO_2), which reduces the amount of usable syngas.

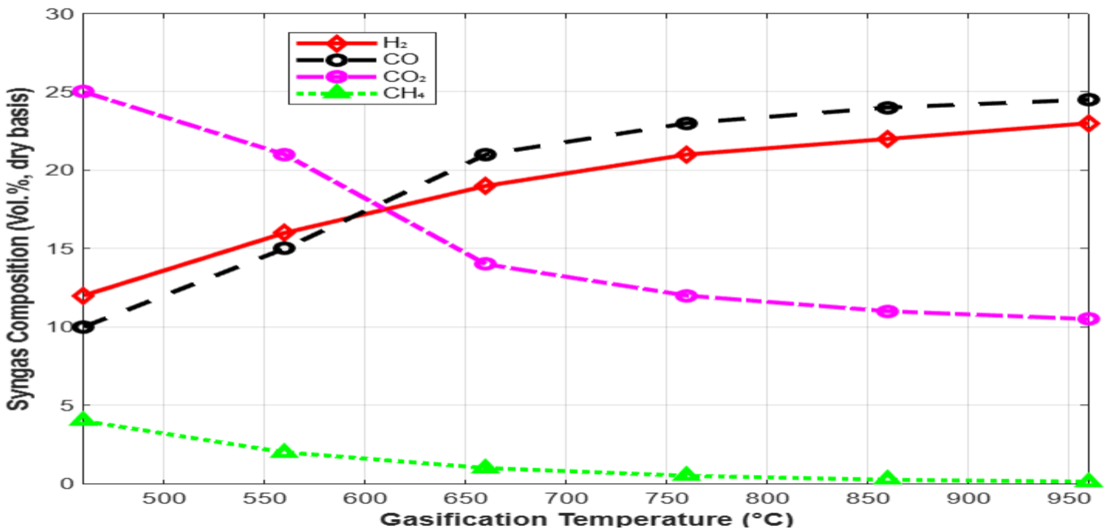

Figure 6.4 Factor affecting of Gasification Temperature on Compositions of producer gas for corn cob

On the other hand, at lower gasification temperatures, the conversion of biomass into syngas is less efficient. More unreacted hydrocarbons, including methane (CH_4), remain in the gas mixture, and the overall syngas yield decreases. Lower temperatures also promote the water-gas shift reaction, which converts CO into CO_2 and H_2. While this reaction increases hydrogen levels, it also reduces the amount of CO, which is essential for maintaining a high-energy syngas composition. Finding the right balance in gasification temperature is essential too low, and the process is inefficient; too high, and valuable syngas components are lost to excessive oxidation. Increase the temperature ensures better syngas production, improved energy efficiency, and a composition suitable for applications like power generation and synthetic fuel production.

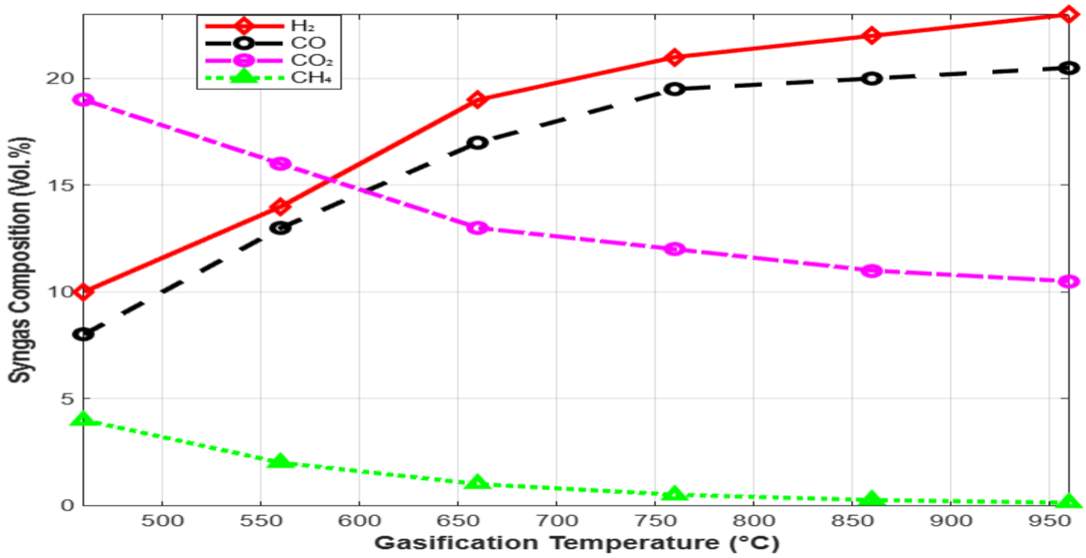

Figure 6.5 Factor affecting of Gasification Temperature on Compositions of producer gas for wheat straw

6.2.3 Effect of Equivalence Ratio

The equivalence ratio (ER) is a key parameter in gasification that directly affects syngas composition and its lower heating value (LHV). At lower ER values, the process operates under fuel-rich conditions, promoting the production of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4), which contribute to a higher syngas energy content. As ER increases, more oxygen is introduced, shifting reactions toward combustion, leading to higher carbon dioxide (CO_2) formation while reducing the concentration of combustible gases, ultimately lowering the LHV of the syngas.

6.2.3.1 Effect of Equivalence Ratio on syngas Production

The equivalence ratio (ER) is a key factor in shaping the composition of syngas, as it regulates how much oxygen is supplied during the gasification process. As shown in Figure 6.6 and 6.7, when the ER for corn cob raise from 0.24 to 0.4, the amounts of CO_2 also increased going from 6.34% to 13.97%. At the same time, we observe a significant drop in the concentrations of CO, H_2, and CH_4, which decrease from 28.68% to 19.80%, from 25.46% to 20.67%, and from 0.25% to 0.085%. Similar patterns are shown with wheat straw; increasing the ER from 0.24 to 0.4 leads to increases in CO_2 from 10.85% to 18.72%. Conversely, CO, H_2, and CH_4 levels decrease from 23.99% to 16.42%, from 28.02% to 23.87%, and from 0.21% to 0.05%. These observations suggest that as we raise the ER, we introduce more oxygen into the system, resulting in more complete oxidation and thus more CO_2 production, which ultimately reduces syngas yield.

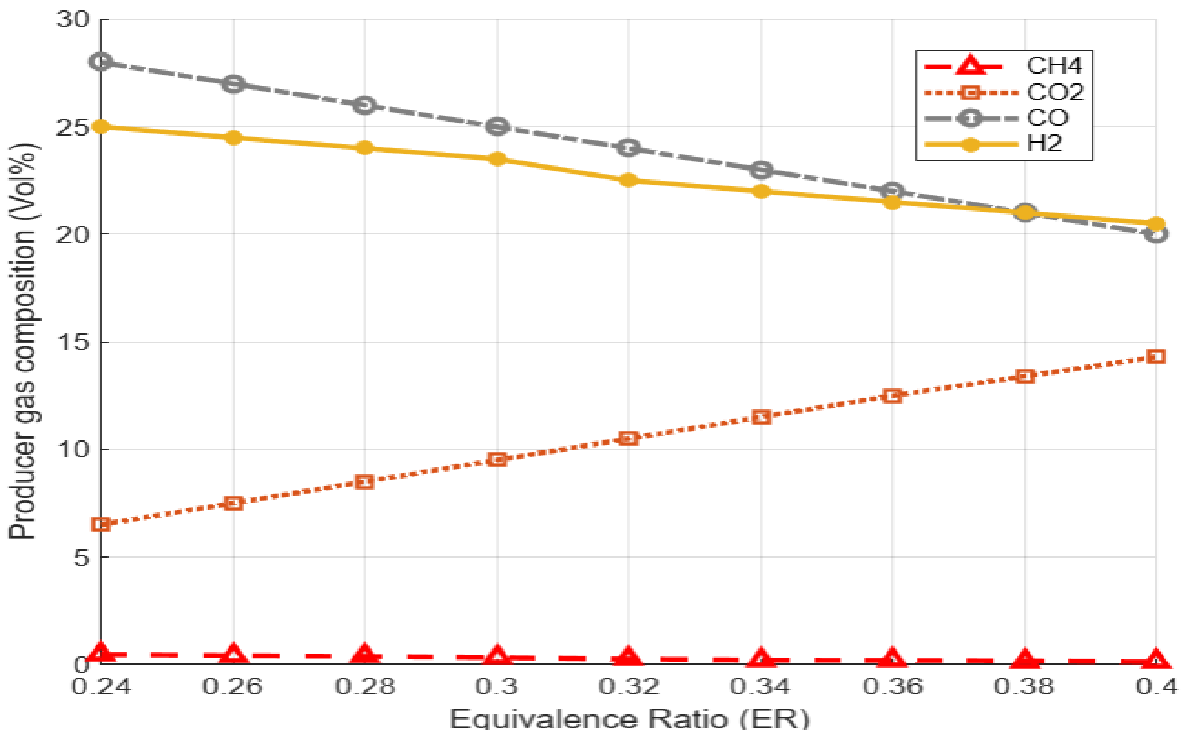

Figure 6.6 Factor affecting of equivalence ratio on compositions of producer gas for corn cob

This aligns with earlier studies conducted by (Kumar et al., 2016), (Vyas, 2021), and (Kumar Chauhan et al., 2023)which also noted similar shifts in syngas composition with increasing ER. As the ER rises, the concentration of CH_4 continues to remain low and keeps decreasing, while H_2 levels drop too, as the process shifts toward more complete oxidation. The increase in CO_2 levels alongside the decrease in CO and H_2 indicates a transition from a gasification-focused process to one that leans more toward combustion. To better understand these trends, we can look at several thermochemical reactions at play. For instance, the in Equation 4-9 is exothermic, meaning that lower equivalence ratio and temperature conditions favour the generation of CO. Similarly, in the Equation 4-12 also favours the production of CO and H_2 by consuming more char and water. On the other hand, in the Equation 4-12 is an endothermic reaction, which means that ER rise, the production of CH_4 and H_2 decrease.

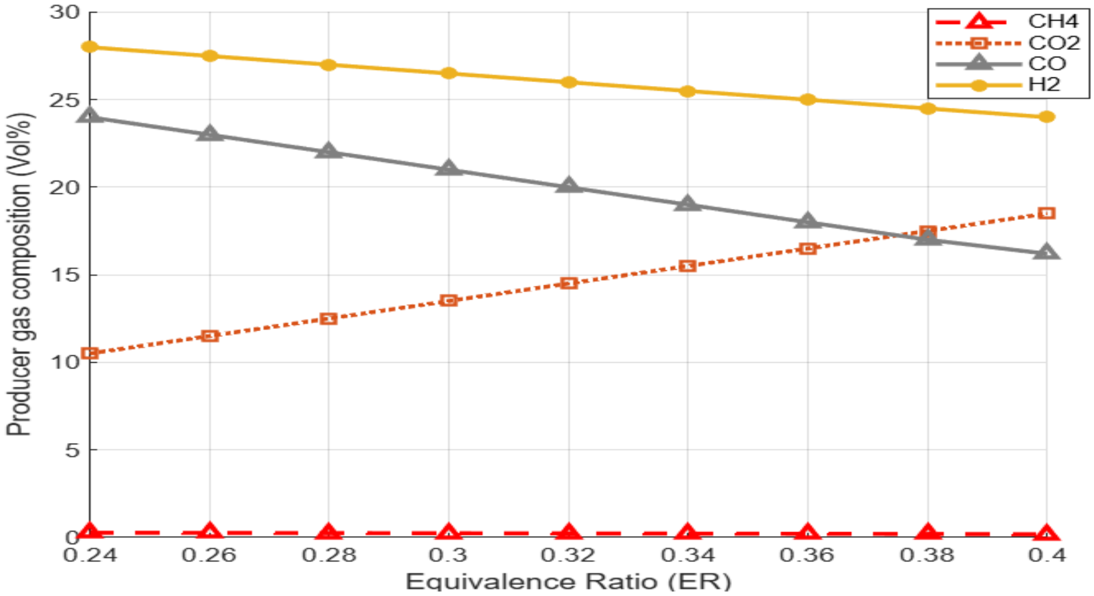

Figure 6.7 Factor affecting of equivalence ratio on compositions of producer gas for wheat straw

6.2.3.2 Summary of Equivalence Ratio affecting on Syngas Composition

The Table shown the Equivalence Ratio (ER) affected the composition of producer gas for corn cob and wheat straw during gasification. As ER rise from 0.24 to 0.40, combustible gases, CO, CH_4 and H_2 show a consistent decrease in volume percentage for both type of biomass, illustrated that higher oxygen availability promotes further oxidation of these gases, reducing their presence in the producer gas. In contrast, the non-combustible gases CO_2 increase with ER, as more oxygen leads to greater combustion.

Table 6:2 Effect of equivalence ratio on producer gas

Gas Component	Increasing ER (0.24-0.40)	Corn Cob	Wheat Straw
CH_4	Decreases	0.25 to 0.05	0.21 to 0.04
H_2	Decreases	25.46 to 20.67	28.02 to 23.87

CO	Decrease	28.69 to 19.80	23.99 to 16.42
CO_2	Increases	6.49 to 13.95	10.85 to 18.72

These patterns summarized in Table 6:2 the influence of feedstock type and equivalence ratio on producer gas.

6.2.3.3 Effect of Equivalence Ratio on Lower Heating Values of Syngas

As the equivalence ratio (ER) rise from 0.24 to 0.40 the lower heating value (LHV) of producer gas may be decreases for corn cob from 5.31 to 3.92 MJ/NM^3 and for wheat straw from 4.91 to 3.83 MJ/Nm^3. At lower ER values, the gasification process operates under fuel-rich conditions, leading to a higher concentration of combustible gases, as hydrogen (H_2), carbon monoxide (CO), and methane (CH_4). These gases contribute significantly to the energy content of syngas, resulting in a higher LHV.

However, as the ER rise, much oxygen is introduced into the system of gasifier, shifting the reaction towards combustion rather than gasification. This leads to an increased production of carbon dioxide (CO_2) and decreasing CO and H_2, thereby reducing the overall lower heating value of the producer gas.

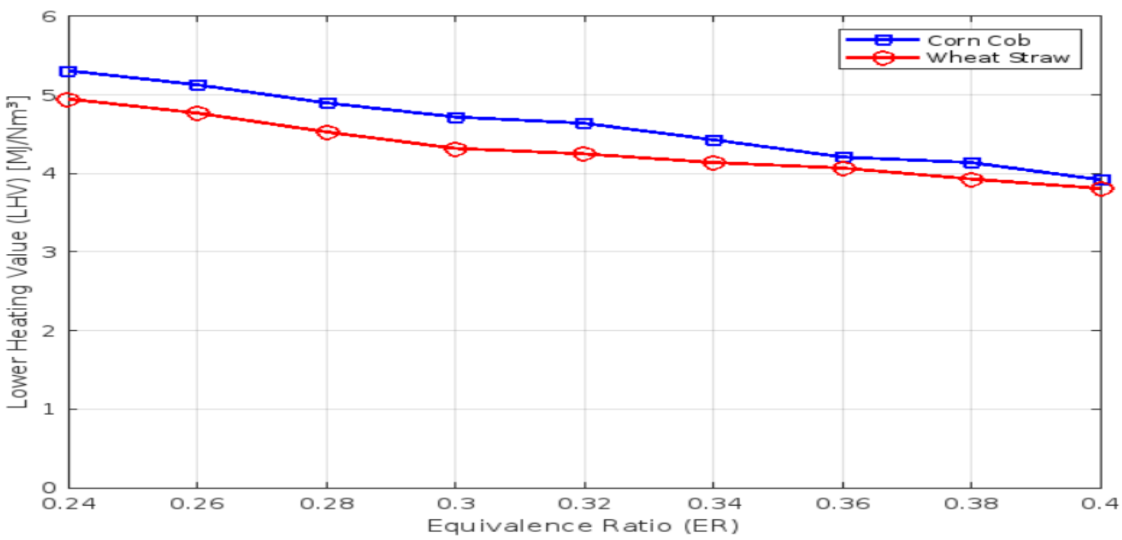

Figure 6.8 Factor affecting of equivalence ratio on Lower heating values for corn cob and wheat straw

6.3 Exergy Efficiency

Exergy efficiency is simply the ratio of the sum of exergy of the useful syngas components to the exergy of input biomass at a specified reactor temperature and equivalence ratio. Higher exergy efficiency reflects higher exergy quality used in the system. In practical science, 100% exergy efficiency is not possible due to internal and external exergy losses due to irreversibility. Figure 6.9 shows variation of exergy efficiency with temperature for the gasifier under study. A maximum ratio of 0.744 is obtained at 750°C and a minimum of 0.692 is obtained at 600°C for corn cob and maximum ratio of 0.729 is obtained at 750°C for wheat straw and a minimum of 0.678 is obtained at 600°C for wheat straw. The MC of corn cob and wheat straw were 6.13% and 6.03% respectively; and their ER also 0.32.

The stoichiometric thermodynamic equilibrium model was integrated with an exergy analysis by certain researchers (Karamarkovic and Karamarkovic, 2010; Saleh and Samad, 2021; Silva et al., 2019; Z. Wang and Baniotopoulos, 2023). A component of their analysis is the assessment of exergy efficiency as presented in Section 4.4. As a result, they determined that exergy efficiency reduces as decrease temperature, and at specific values of ER and MC.

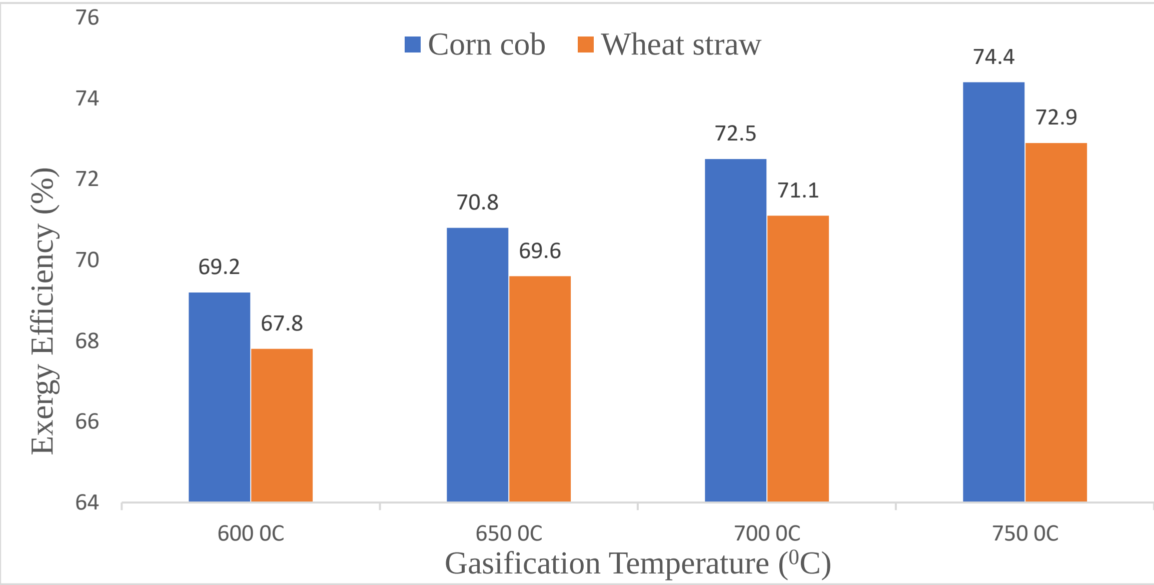

Figure 6.1 Exergy efficiency corn cob and wheat straw

6.4 Experimental Observations of Throat Updraft Gasifier

A series of experimental test and readings have been made for a period of a week to studied the behaviour of the throated updraft gasifier. The experiments undertaken during the gasification of corn cob and wheat straw biomass include reading gasification temperature and analysing syngas composition. In this section various results obtained from the experimental result is presented.

6.4.1 Gasification of Biomass Feedstock

Gasification of Corn Cob and wheat straw in a throat updraft gasifier shows the important effects of pellet size on gasification behaviour and syngas quality. Experiments conducted using feedstock pellets with diameters ⌀10 mm, ⌀16 mm, and ⌀20 mm has shown that smaller pellets (⌀10 mm) tend to enhance the uniformity of temperature distribution and increased surface area, which resulting in higher carbon conversion efficiency and increased production of combustible gases, CO and H_2. In contract, larger pellets (⌀20mm) decreased surface area to volume ratio, which lead to consumed more time of combustion, and heightened tar formation due to incomplete gasification. The intermediate size (⌀16 mm) frequently occurs a balance between flow permeability and residence time, leading to operation that is relatively stable and moderate syngas quality. Hence, pellet size plays a significant role in increase gasifier performance, particularly in terms of temperature profile, syngas composition, and tar production.

6.4.1.1 Temperature Profile within in the Gasifier

The three figures 6.10, 6.11 and 6.12 illustrates the temperature changes across five zones, T_1 to T_5 of a gasifier over time using compressed air with three different corn cob pellets sizes; ⌀10 mm, ⌀16 mm and ⌀20mm. In these cases, the temperatures rise in all zones, but there are noticeable differences in temperature ranges and heating behaviour. For the ⌀10 mm corn cob, the temperature ranges are 217–479.6 °C at T_1 (ash zone), 261–705 °C at T_2 (reduction zone), 432–915.23 °C at T_3 (oxidation zone), 416–864.8 °C at T_4 (pyrolysis zone), and 165–341°C at T_5 (drying zone) in 45 munities.

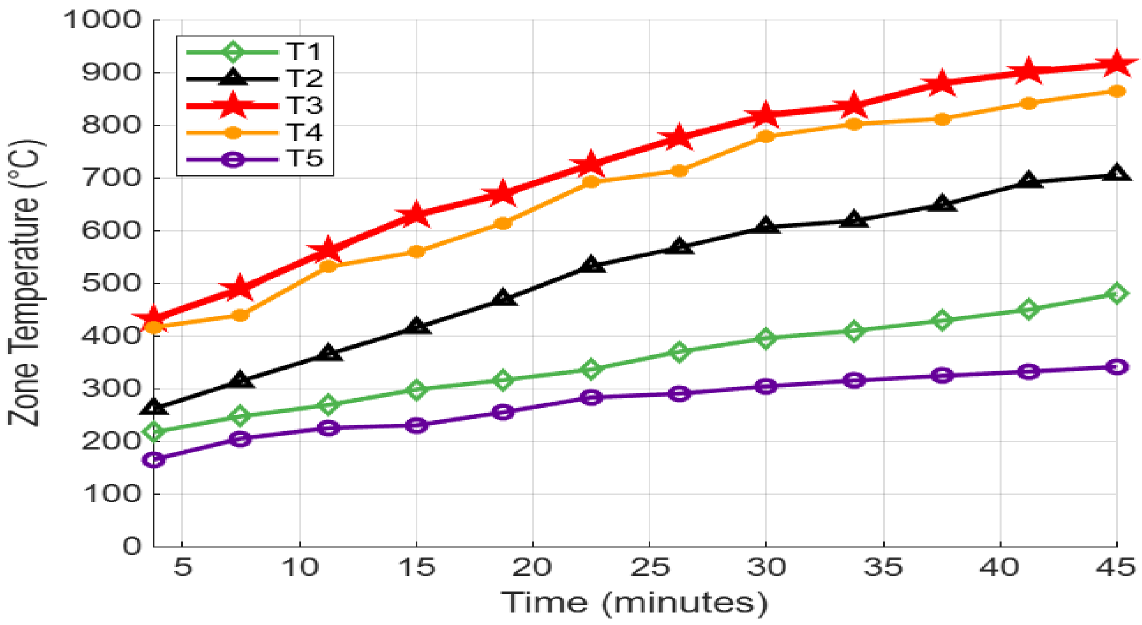

Figure 6.2 Gasifier Temperature with time for ⌀10 mm corn cob used compressed air

In comparison, the ⌀16 mm pellet exhibits slightly higher final temperatures, with ranges of about 237–496 °C at T_1, 270–715 °C at T_2, 440–923 °C at T_3, 420–888 °C at T_4, and 175–350 °C at T_5 with 60 minutes duration time. For ⌀20mm temperature ranges from T1 to T5; 255-512°C, 307-744°C, 458-936°C, 442-917°C, 183-365°C respectively and its duration time 70 minutes. The ⌀10 mm pellet of corn cob is the best comparison with ⌀16 mm and ⌀20 mm pellets for gasification and syngas production primarily due to its higher surface area to volume ratio**,** which significantly enhances both heat transfer and reaction kinetics within the gasifier. Smaller particle sizes allow heat to penetrate more rapidly and uniformly, leading to quicker drying, pyrolysis, oxidation, and reduction reactions.

Additionally, the ⌀10 mm corn cob reaches high temperatures in a shorter duration of time**,** which can reduce energy consumption during start up and increase overall process efficiency. These characteristics make the ⌀10 mm feedstock more reactive and efficient, enabling higher syngas yield in a shorter residence time**.** The Figures 6.13, 6.14, and 6.15 shown the different of zone temperatures (T_1 to T_5) over time during gasification utilizing ⌀10 mm, ⌀16 mm, and ⌀20 mm wheat straw pellets. These Figures represents a variations pellet size and how the temperature evolves in different zones of the gasifier.

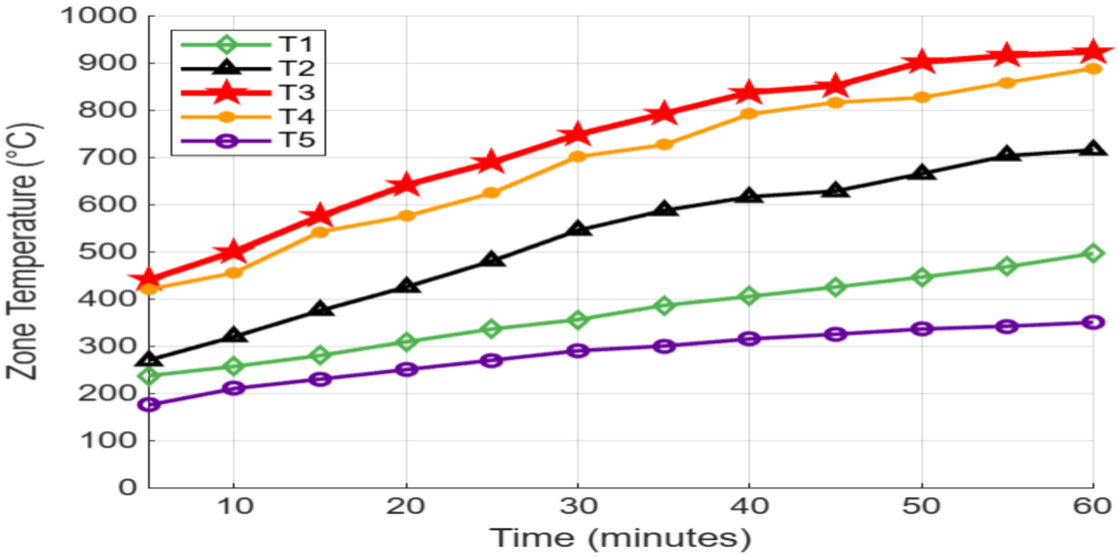

Figure 6.3 Gasifier Temperature with time for ⌀16 mm corn cob used compressed air

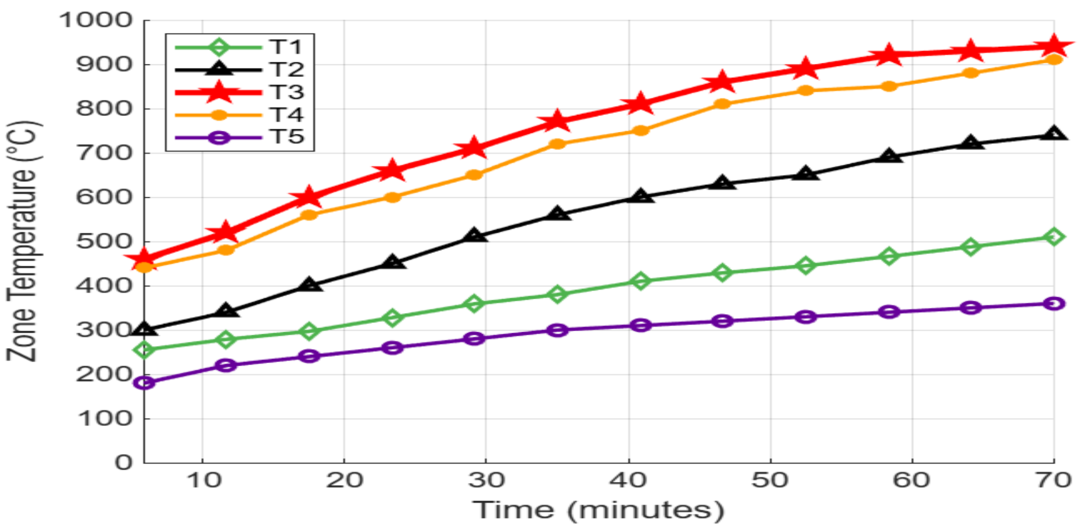

Figure 6.4 Gasifier Temperature with time for ⌀20 mm corn cob used compressed air

Figure 6.13, illustrated (⌀10 mm pellets), the temperatures in all zones steadily rise over the 45-minute duration. Oxidation zone, T_3 consistently and read the highest temperatures, reaching at 831°C, while the drying zone, T5 shows the lowest temperatures, read until 328°C. This shows effective heat distribution and rapid gasification efficiency due to the smallest pellet size, which facilitates faster heat transfer and combustion. The Figure 6.14, shows (⌀16 mm pellets) extends the timeline to 50 minutes and shows a similar upward trend in all zones. But, compared with the 10 mm pellets, the rate of temperature increase is slightly slower, and the maximum temperatures reached are marginally lower, with T_3 peaking around 865°C. The Figure 6.15 shows (⌀20 mm pellets), the heating profile continues to show consistently rise, but the temperature rise is the slowest among the three cases. Even at 60 minutes, the temperatures remain slightly lower than the ⌀10 mm and ⌀16 mm scenarios, with T_3 reaching just at 900°C.

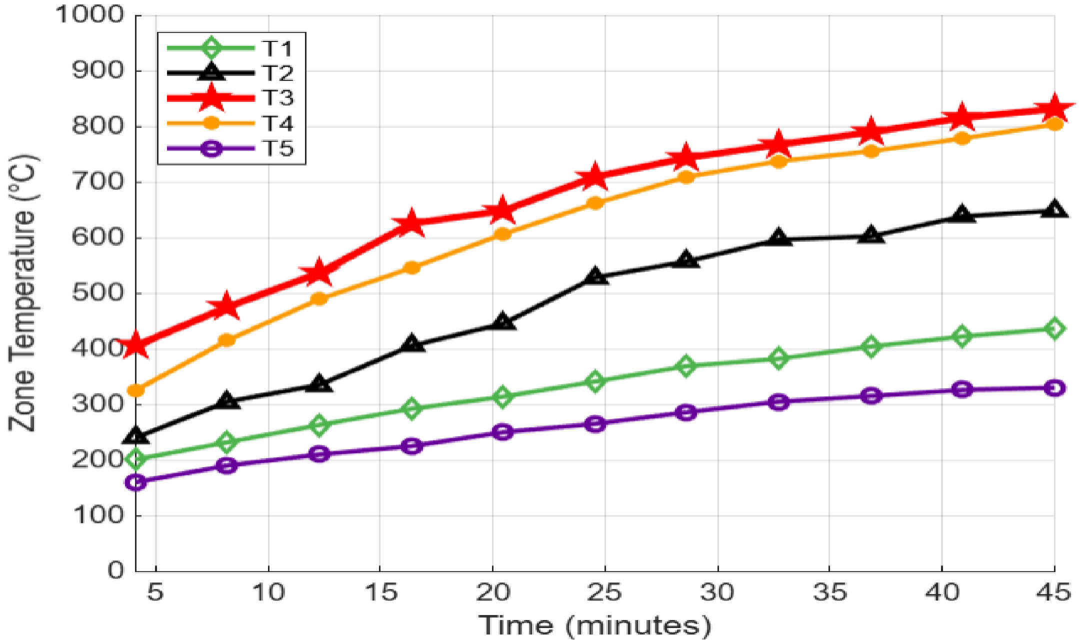

Figure 6.5 Gasifier Temperature with time for ⌀10 mm wheat straw used compressed air

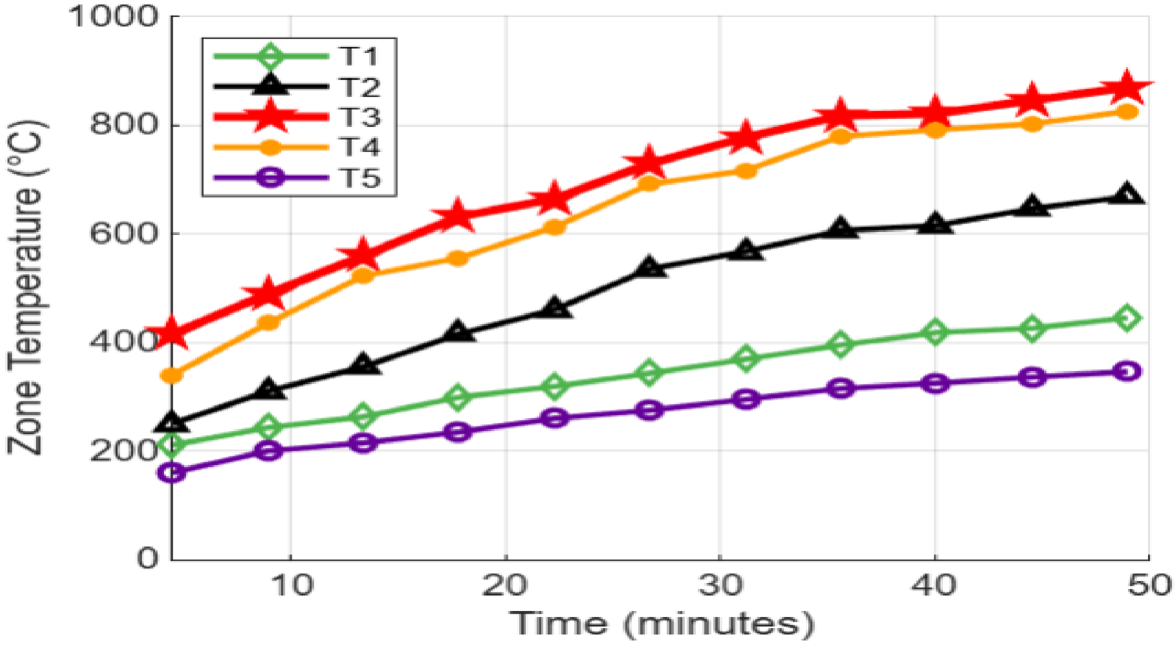

Figure 6.6 Gasifier Temperature with time for ⌀16 mm wheat straw used compressed air

This implies that the largest pellet size has the most thermal inertia, which decrease the gasification and slows down the process of gasification. Summary, the smallest pellet (⌀10 mm) exhibit the fastest and most gasification efficient response, achieving higher temperatures in shortest times, which is beneficial for rapid gasification. In contrast, the largest pellet (⌀20 mm) delay the process due to the lowest surface area to volume ratio, made them lest efficient for quick thermal conversion in gasifiers. The trend across the Figures 6.13, 6.14, and 6.15 confirms that pellet size significantly affected gasifier performance, particularly in temperature development over time taken.

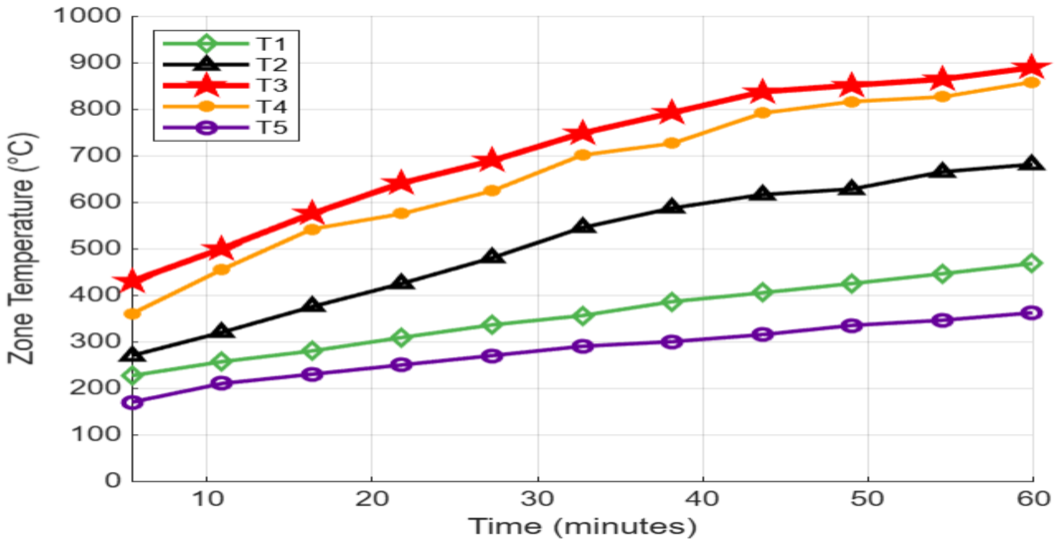

Figure 6.7 Gasifier Temperature with time for ⌀20 mm wheat straw used compressed air

6.4.1.2 Flame Intensity

Figure 6.16 shown, a visual investigation of the syngas flame during gasification of wheat straw and corn cob shown significant variations in flaming characteristics that correlate with their respective calorific values and combustion quality. Wheat straw shown a stable, moderately intense flame with consistent burning, indicative of a good quality syngas with reasonable energy content, although occasional fluctuations were observed due to its higher ash content and fibrous structure, which can partially obstruct gas flow. In comparison, corn cob produced a bright, steady, and more vigorous flame, reflecting a higher calorific value and more efficient combustion behaviour. This is likely due to its denser structure which promote smoother gas flow and better gasification. According to visual assessment, the flame quality for corn cob and wheat straw can be rated as very good.

Figure 6.8 Comparison of flame intensity, (a) for corn cob ⌀10 mm pellet, (b) for corn cob ⌀20 mm pellet, and (c) for wheat straw ⌀10 mm pellets

6.4.1.3 Composition Producer Gas

The composition of producer gases was significantly effect depend on biomass type, pellet size, and moisture content. In terms of composition, the syngas primarily consists of carbon monoxide (CO), methane (CH_4), and carbon dioxide (CO_2). Experimental analysis indicate that CO is the dominant combustible gas, typically range between 14.50 to 19.85%, while CH_4 is present in smaller amounts, less than 0.5%. CO_2 levels fluctuated between 11.50 to 13.50%, depending on operational conditions and feedstock characteristics. When comparing biomass types, corn cob higher CO yields than wheat straw due to its lower ash content shown Figure A.4, and better thermal reactivity, enhancing overall syngas quality. The size of pellet is also playing a crucial role; the smallest pellets (⌀10 mm) tend to produced higher temperatures and faster reaction rates, resulting to increased CO production and reduced CO_2 due to more effective gasification. Comparison, largest pellets (⌀20 mm) result which consumed the most time to conversion efficiency, CO and CO_2 output content. The feedstock utilized had moisture content for corn cob and wheat straw 6.18%, and 6.03% respectively.

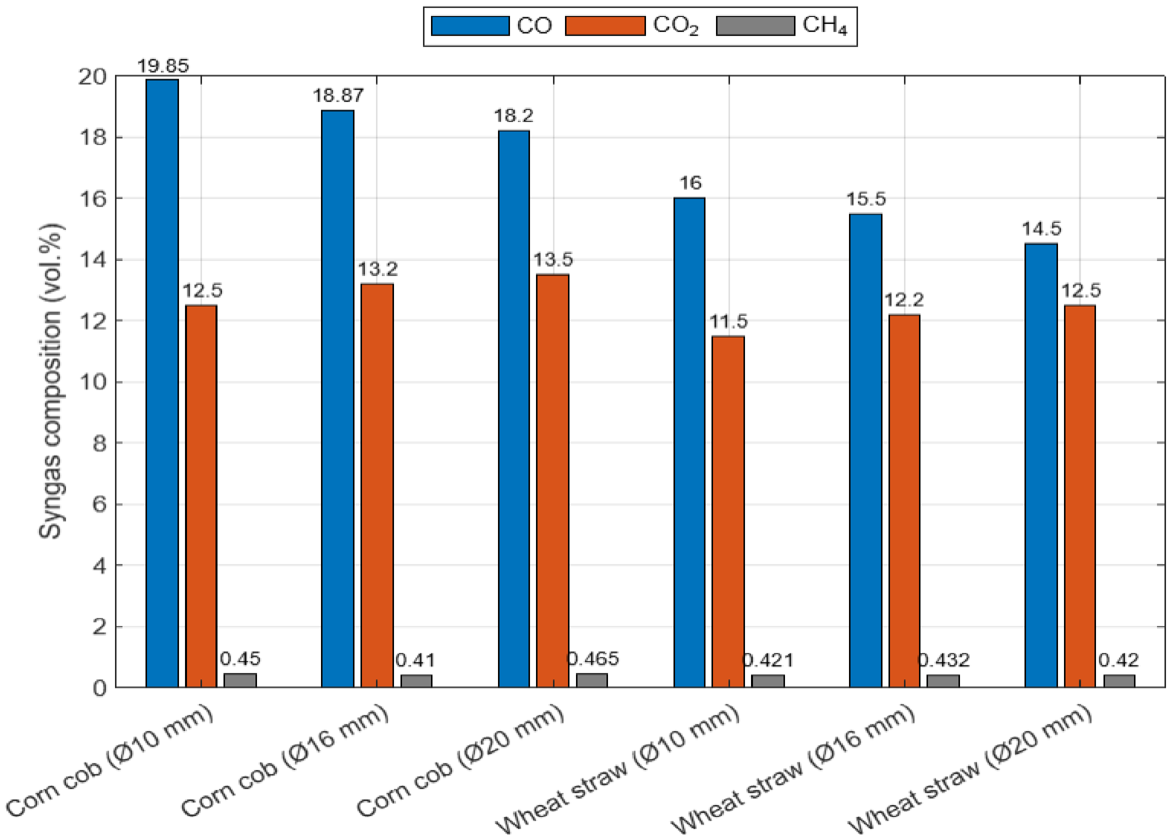

Figure 6.9 Producer gas results

6.5 Comparison of Present Work with Previous Research

Producer gas composition for corn cob and wheat straw with previous experimental and modelling research (Vyas, 2021), (Kumar et al., 2016), and (Silva et al., 2019). The Figure 6.18 shown, summarizes the volumetric compositions of CO, CO_2, H_2, and CH_4 for present work and different previous research. The amount of air supplied into the system determines how well the gasification process performs, and this may be determined using the equivalency ratio. The volume fraction of hydrogen, carbon monoxide, and methane generally decreases while the volume fraction of carbon dioxide, water, and nitrogen increases as a result of a rise in air inlet on gasification systems, according to studies (Kumar et al., 2016; Silva et al., 2019).

The biomass that has high ER and MC is less CO and more CO_2 produced illustrated in Table 6:3, but, inversely correlated with the volume percentage on H_2 concentration (Silva et al., 2019). The more oxygen is available this process means in gasifier nearly completely combustion propensity to produce more CO_2 and H_2O (Silva et al., 2019). So, a reduce of combustible gas results on reduce in LHV of syngas. The equilibrium reactions that take place in a gasification system are influenced by temperature. The model shows a tendency for the volume fractions of carbon dioxide decrease while; hydrogen and carbon monoxide to increase as the temperature rises, and vice versa, as the ER increases (Silva et al., 2019).

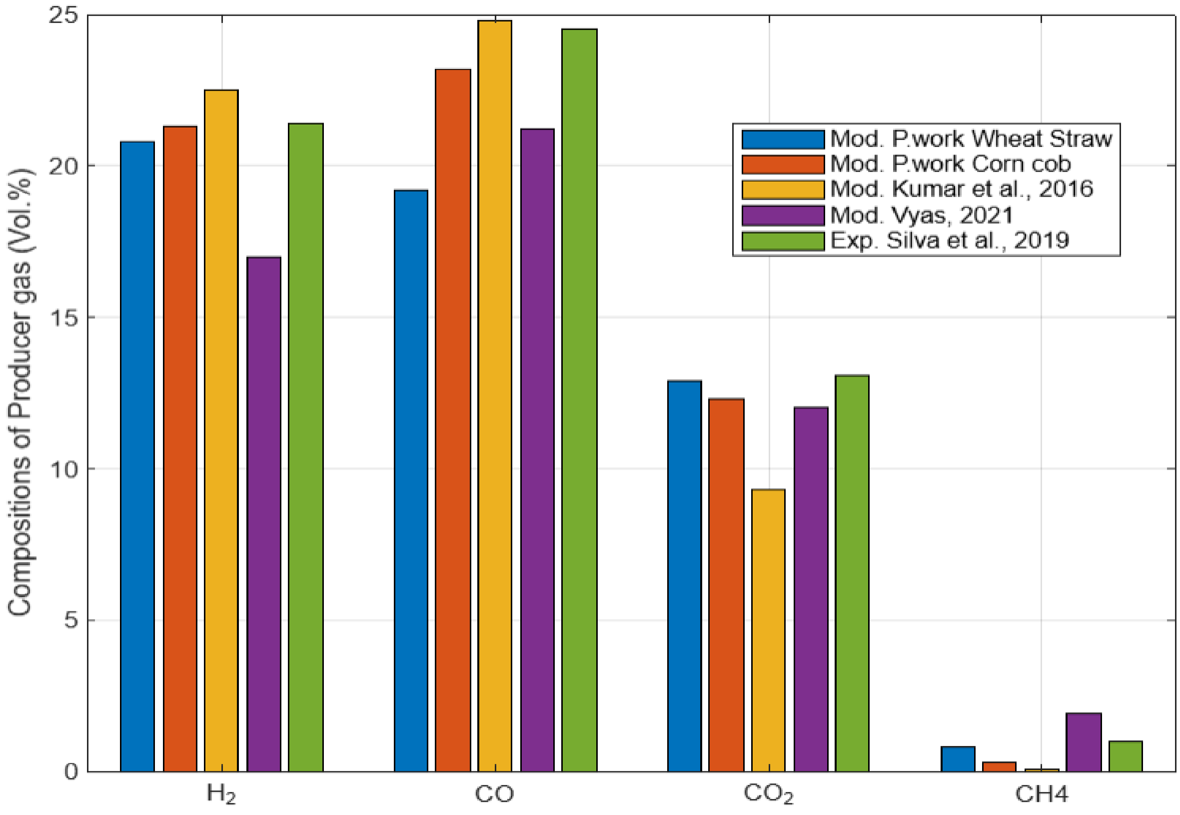

Figure 6.10 Comparison of present work with previous research

Table 6:1 General effects of the gasification process

Parameter	Syngas Composition				LHV
	CO	CO_2	H_2	CH_4	
MC rise	reduce	rise	rise	rise	reduce
Temperature rise	rise	reduce	rise	reduce	rise
ER rise	reduce	rise	reduce	reduce	reduce

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

This study presented an integrated modelling and experimental investigation of a throated updraft gasifier fuelled by two agricultural residues corn cob and wheat straw. The objective was to evaluate the system's performance under varying process conditions and to determine the suitability of these feedstock for sustainable syngas production. This study began with a conducted description of the biomass feedstocks, such as ultimate and proximate analyses, and calorific value determination. These inputs fed into a thermodynamic equilibrium model adopt using MATLAB to simulate the effects of moisture content, gasification temperature and equivalence ratio (ER) on syngas composition and energy contents. Experimental investigation was conducted using pellets of different diameters (⌀10 mm, ⌀16 mm, and ⌀20 mm) to analysis how particle size influences gasification performance. Key parameters such as temperature distribution, syngas composition, flame intensity, and system efficiency were carefully analysed and compared across the two biomass types.

From the modelling analysis:

- Increasing the ER led to a significant reduction in the concentrations of combustible gases (H_2, CO, CH_4), thereby lowering the lower heating value (LHV) of the producer gas.
- Moderate MC in the feedstock enhanced H_2 production through steam-based reactions, but excessive moisture had a negative impact on thermal efficiency and LHV.
- Higher gasification temperatures initially enhanced producer gas quality but excessive heat caused over-oxidation, reducing the yield of combustible gases.
- Efficiency exergy was reached 74.4 at 750°C for corn cob and 72.9% for wheat straw, illustrated efficient conversion of biomass energy into usable chemical energy.
- Syngas produced from corn cob contained 22.31% H_2, 23.81% CO, 12.62%CO_2 and 0.21% CH_4 with an LHV of 5.76 MJ/Nm^3, whereas wheat straw syngas had 19.78% H_2, 21.41% CO, 13.26%CO_2 and 0.68% CH_4 with an LHV of 5.47 MJ/Nm^3.

From the experimental study:

- The temperature profiles of the gasifier were consistent, especially when using ⌀10 mm pellet, which provided the highest thermal responsiveness.
- The smallest pellets produced the most effective heat transfer, therefore particle size was vital and improved gas composition, while larger ones led to higher tar formation and poor gas quality.
- Effective heat propagation from the combustion zone to adjacent zones ensured complete biomass conversion in both feedstocks.
- Producer gas from corn cob and wheat straw for ⌀10 mm pellet size 19.85% CO, 12.5% CO_2 and 0.45% CH_4 and 19.2% CO, 12.1%CO_2 and 0.42% CH_4 respectively.
- The flame quality for both feedstocks were very good characteristics
  was generated. Also, the gasifier performed well overall considering these feedstocks.

7.2 Recommendations

While the current study has successfully demonstrated the feasibility and effectiveness of biomass gasification using agricultural residues, several areas require further research and development to optimize performance and operational reliability. The following recommendations are proposed:

- The thermodynamic equilibrium model was the fundamental feedstock biomass simulation model used in this study; however, future studies should focus on using different methods, such as the ANN model, the kinetics model, which takes reactor geometry into consideration, and software-based simulations like CFD, which predicted the temperature and gas yield surrounding the reactor.
- The gasification of agricultural leftovers, specifically maize cob and wheat straw, was the main focus of the present study. It is recommended that a larger variety of agricultural biomass resources be investigated for syngas production in future research.
- Future studies should concentrate on investigating effective methods for the capture, store, and preserve of the produced syngas to improve its usability and ensure a stable supply for downstream energy application

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A. APPENDIX

A.1 Tables and figures of data for various calculations and graphs

Table A.1 The value of Δhf0 (kJ/mol) and coefficients of the empirical model for Δgf,T,i0 (kJ/mol)

Gas	Δh_f^0 (kJ/mol)	**a**[10^{-2}]	**b**[10^{-6}]	**c**[10^{-9}]	**d**[10^{-12}]	**e**[10^{2}]	**f**	**g**[10^{-2}]
CO	-110.5	0.5619	-1.19	6.383	-1.849	-4.891	0.868	-6.131
CO_2	-393.5	-1.95	3.122	-2.448	6.946	-4.891	5.27	-12.07
H_2O	-241.8	-0.895	-3.672	5.209	-1.478	0.0	2.868	-1.722
CH_4	-74.8	-4.62	1.13	1.139	-6.647	-4.891	14.11	-22.34

Table A.2 Specific heat at constant pressure ideal gas temperature relations (Karamarkovic & Karamarkovic, 2010)

Species	$C_{p,j} = \frac{\text{kJ}}{\text{kmol}\cdot\text{K}}, \quad \varphi = \frac{T(\text{K})}{100}$	Temperature range(K)	Error
CO	$c_p = 69.145 - 0.7046\varphi^{0.75} - 200.770\varphi^{-0.5} + 176.761\varphi^{-0.75}$	300-2400	0.42
CO_2	$c_p = -3.735 + 30.529\varphi^{0.5} - 4.103\varphi + 0.0242\varphi^2$	300-2400	0.19
H_2O	$c_p = 143.050 - 183.541\varphi^{0.25} + 82.751\varphi^{0.5} - 3.699\varphi$	300-2400	0.43
CH_4	$c_p = -672.870 + 439.741\varphi^{0.25} - 24.875\varphi^{0.75} + 323.881\varphi^{-0.5}$	300-2400	0.15
H_2	$c_p = 56.505 - 702.740\varphi^{-0.75} + 1165.000\varphi^{-1} - 560.701\varphi^{-1.5}$	300-2400	0.60
O_2	$c_p = 37.432 + 0.0201\varphi^{1.5} - 178.57\varphi^{-1.5} + 236.88\varphi^{-2}$	300-2400	0.43
N_2	$c_p = 39.060 - 512.79\varphi^{-1.5} + 1072.7\varphi^{-2} - 820.40\varphi^{-3}$	300-2400	0.30

Table A.3 Factor affecting of moisture contents for wheat straw with its producer gas compositions and LHV

MC (%)	CH_4 (Vol.%)	CO_2 (Vol.%)	CO (Vol.%)	H_2 (Vol.%)	LHV (MJ/Nm^3)
5	0.07	10.49	18.47	21.03	4.85
7	0.14	11.53	17.27	21.94	4.779
9	0.21	12.38	16.54	22.76	4.60
11	0.26	12.95	14.79	23.60	4.53

13	0.33	13.73	13.11	24.36	4.45
15	0.39	14.54	12.70	25.04	4.37
17	0.45	15.47	12.07	25.84	4.29
19	0.51	16.51	11.50	26.75	4.11
21	0.56	17.48	10.30	27.58	4.02
23	0.59	18.38	8.77	28.23	4.00
25	0.63	19.09	6.29	28.81	3.95

Table A.4 Factor affecting of moisture contents for corn cob with its producer gas compositions and LHV

MC (%)	CH_4 (Vol.%)	CO_2 (Vol.%)	CO (Vol.%)	H_2 (Vol. Vol.%)	LHV (MJ/Nm^3)
5	0.08	10.12	21.56	21.63	5.15
7	0.13	10.99	20.36	22.07	5.08
9	0.19	12.39	19.12	22.82	5.00
11	0.23	12.81	18.67	23.60	4.93
13	0.28	13.64	17.58	24.39	4.85
15	0.33	14.50	15.66	25.20	4.77
17	0.37	15.68	14.92	25.83	4.70
19	0.41	16.49	13.54	26.87	4.60
21	0.46	17.22	11.63	27.54	4.52
23	0.51	17.77	10.58	28.53	4.43
25	0.53	18.55	9.60	29.34	4.34

Table A.5 Factor affecting of Equivalence ratio for corn cob with its producer gas compositions and LHV

ER	CH_4 (Vol%)	CO_2 (Vol%)	CO (Vol%)	H_2 (Vol%)	LHV (MJ/Nm^3)
0.24	0.25	6.46	28.69	25.46	5.31
0.26	0.23	7.65	27.21	24.15	5.13
0.28	0.19	9.30	26.34	24.20	4.90
0.30	0.15	9.82	25.13	23.35	4.72
0.32	0.11	10.45	24.26	23.20	4.64
0.34	0.09	11.38	23.34	22.45	4.43
0.36	0.07	12.26	22.41	21.28	4.21

0.38	0.06	13.30	21.17	21.30	4.14
0.40	0.05	13.97	19.80	20.67	3.92

Table A.6 Factor affecting of equivalence ratio for wheat straw with its producer gas compositions and LHV

ER	CH_4 (Vol%)	CO_2 (Vol%)	CO (Vol%)	H_2 (Vol%)	LHV (MJ/Nm^3)
0.24	0.21	10.85	23.99	28.02	4.91
0.26	0.19	11.25	23.23	27.55	4.74
0.28	0.16	12.42	22.42	27.13	4.53
0.30	0.14	13.51	21.31	26.62	4.32
0.32	0.11	14.43	20.16	26.14	4.25
0.34	0.09	15.35	19.19	25.95	4.14
0.36	0.08	16.13	18.24	25.12	4.07
0.38	0.06	17.26	17.37	24.65	3.93
0.40	0.04	18.72	16.42	23.87	3.83

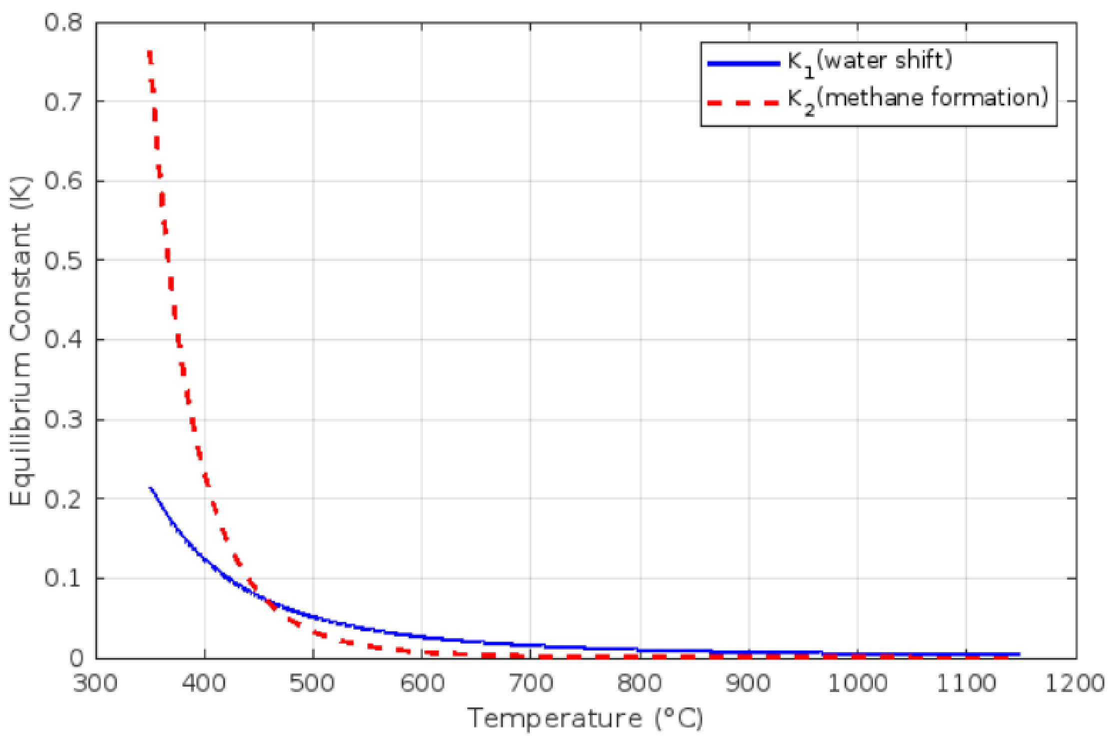


Figure A:1 Variation of equilibrium constants with gasifying temperature

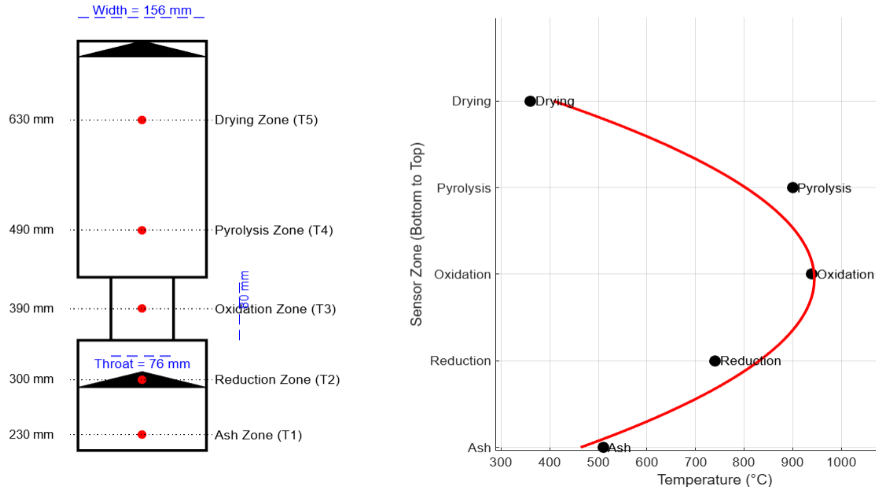


Figure A:2 Distributive temperature on vertical direction of throat updraft gasifier for ⌀20 mm pellet size corn cob used as feedstock

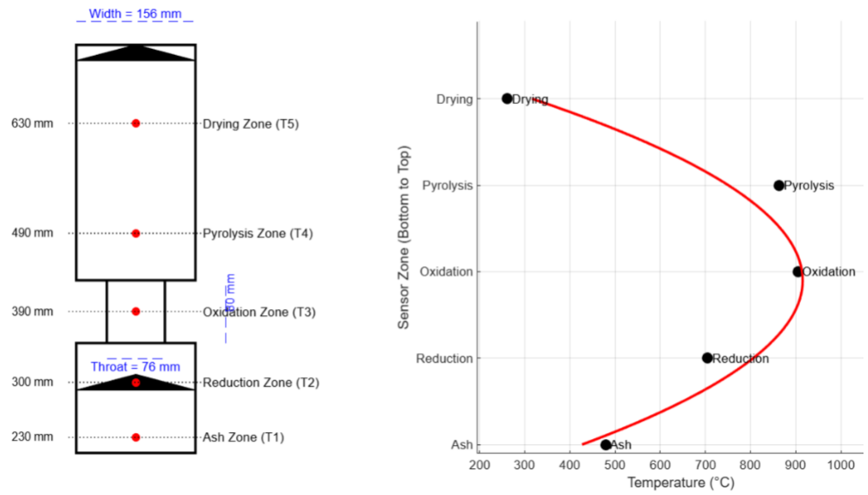


Figure A.3 Distributive temperature on vertical direction of throat updraft gasifier for ⌀10 mm pellet size corn cob used as feedstock

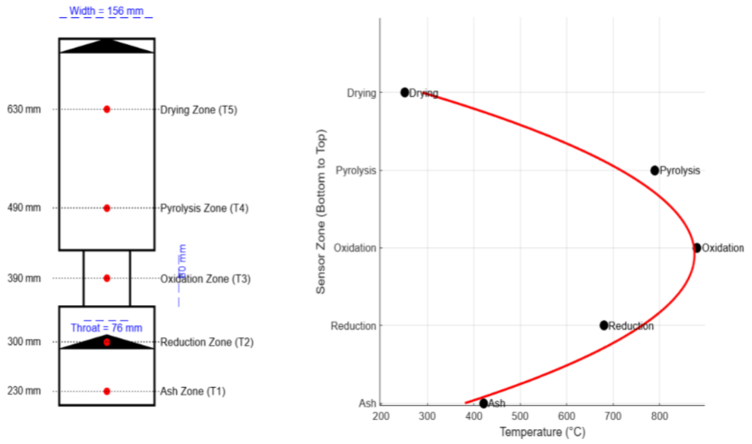


Figure A: 4 Distributive temperature on vertical direction of throat updraft gasifier for ⌀10 mm pellet size wheat straw used as feedstock

A.2 Proximate Analysis of Corn cob and Wheat straw

This analysis was for biomass samples were selected biomass feedstock for this study was conducted, in Geochemical Laboratory Desk at Geological Institute of Ethiopia found in Addis Ababa.

	GEOLOGICAL INSTITUTE OF ETHIOPIA	Doc. Number: GLD/F5.10.2	Version No: 1
	Geochemical Laboratory Desk		Page 1of 1
Document Title:-	Hydrocarbon Analysis Report	Effective date:	Nov. 2022

Customer Name :- Tafari Afessa Moroda

Issue Date:- 02/05/2025

Sample type:-Corn Cob + Wheet Straw

Request No:-GLD/RN/1224/25

Sample Preparation:- 60 Mesh

Report No:- GLD/TR/4708/25

Date Submitted:- 10/04/2025

Number of Sample:- One(01)

Elements to be determined:-(Moisture,Volatile matter, Fixed carbon and Ash), Calories & Sulfur.

Method of analysis:- Proximate Analysis, Adiabatic Calorie Metter and Gravimetric Method.

Collectors' Code	Moisture %	Volatile Matter %	Fixed carbon %	Ash %	Calorific Value cal/gm	sulfur%	Weight of Sample
Corn-01	6.18	76.85	12.97	3.99	3995.66	<0.02	500gm
WS-02	6.03	73.24	10.85	9.89	3272.99	<0.02	300gm

Note: - This result represent only for the sample submitted to the laboratory.

Analysts
Bethelhem Tefera
Duressa Abdisa
Chala Melese
Haimanot Bayeh
Alemayehu Worku

Approved By
Desalew Bitew

Quality Control
Yohannes Getachew

Geochemical Laboratory Desk

Page 1

Figure A:5 Proximate analysis of Corn cob and Wheat straw

A.3 Biomass Preparation

Figure A:7 Biomass preparation

A.4 Throat updraft gasifier prototype

Figure A:8 Visual throat updraft gasifier prototype

A.5 Instrumentation that used for experiment

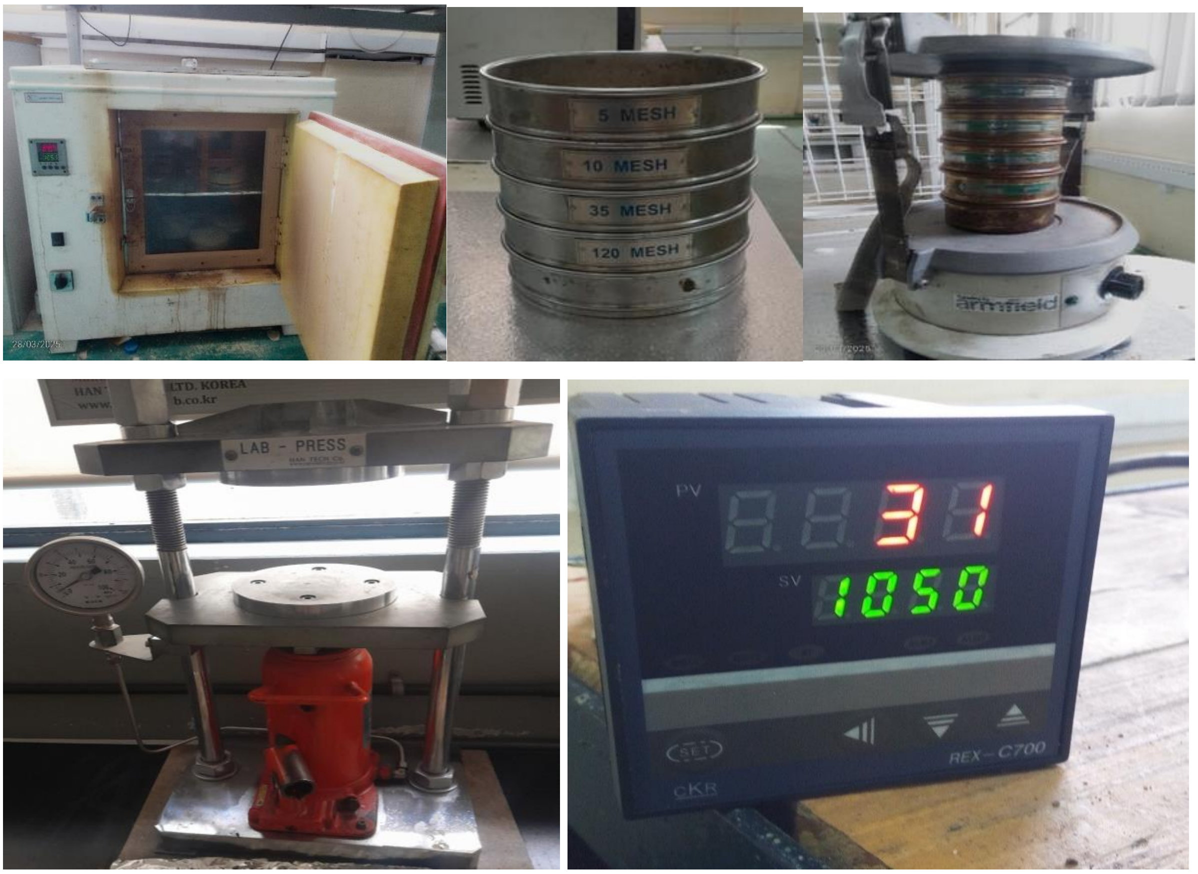


Figure A:9 Instrumentation used for experiment

A.6 Thermocouple Calibration

Calibration of thermocouples is essential to confirm the correct temperature reading and can be calibrated with a standard thermocouple in ASTU thermal laboratory. Calibration test for K-type thermocouple was conducted with Reference thermocouple by using 1litter of water boiling and cooling test for 30 minutes.

Figure A:10 Calibration setup of thermocouples with calibrator

Time (Minutes)	Standard thermocouple read(T1)	K-type thermocouple Read(T2)	Percentage of uncertainty (%) $(\frac{T_1-T_2}{T_1}) * 100\%$
1.	26.9	26.6	1.12
2.	29.1	28.9	0.69
3.	30.4	30.2	0.66
4.	32.8	32	2.44
5.	35.4	34.3	3.11
6.	37.6	37	1.60
7.	39.4	38.8	1.52
8.	42	41.1	2.14
9.	45.9	45.5	0.87
10.	51	49.7	2.55
11.	51.5	51.4	0.19
12.	54	53	1.85
13.	57	56.5	0.88
14.	58.5	57.7	1.37
15.	61.7	61	1.13
16.	62.5	62	0.80
17.	65.6	64.7	1.37
18.	67.4	66.8	0.89
19.	68.7	68.4	0.44
20.	68.7	68.5	0.29
21.	71.4	71.3	0.14
22.	73.7	73.1	0.81
23.	76.2	75.3	1.18
24.	77.7	77.3	0.51
25.	78.9	78.6	1.12
26.	80.5	79.9	0.38
27.	81.3	80.9	0.75
28.	82.4	82	0.49
29.	83.3	83	0.49
30.	84.3	84.2	0.36

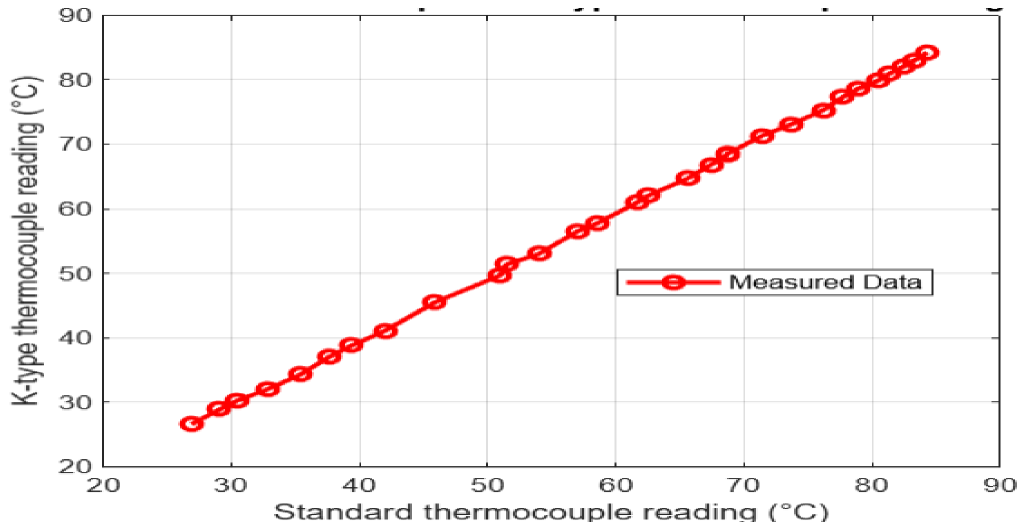


Figure A:11 Measured Vs corrected Temperature

A.7 Drawing of Throat updraft gasifier Parts

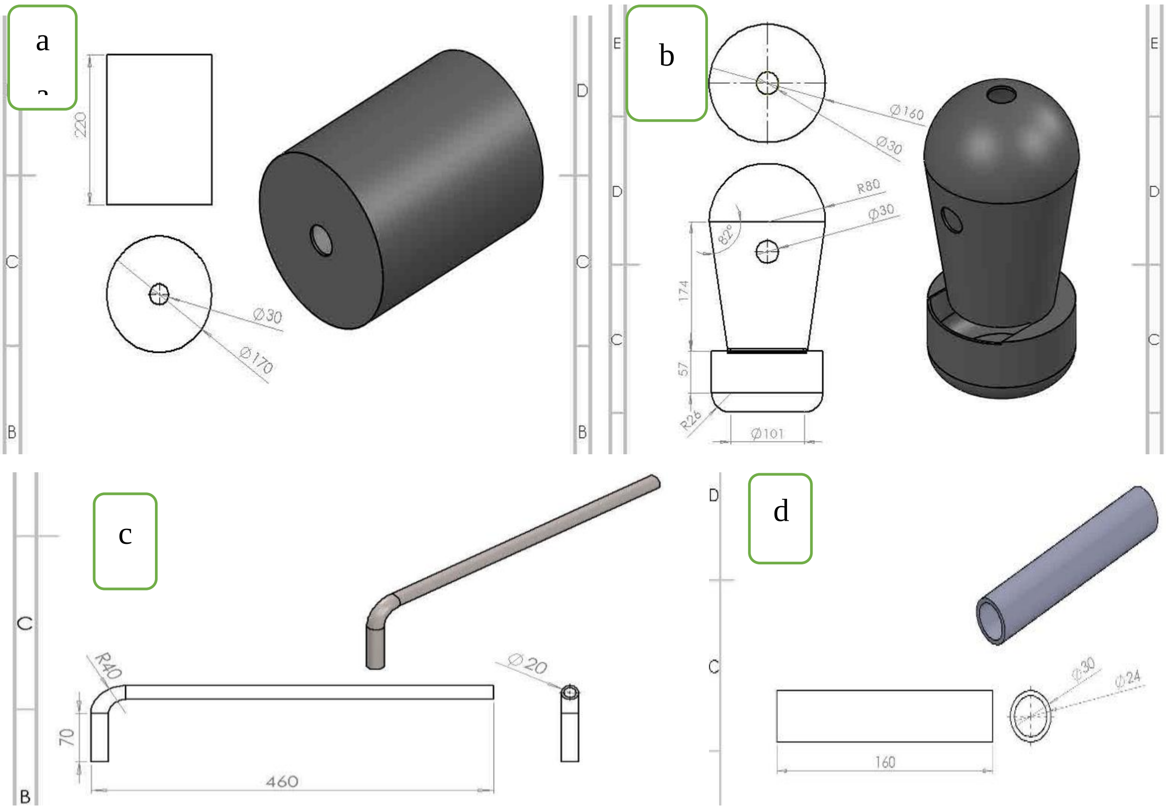


Figure A:12 Components of gasifier (a)suction fan, (b) cyclone separator, (c) preheater pipe line, (d) Fan outlet pipe line

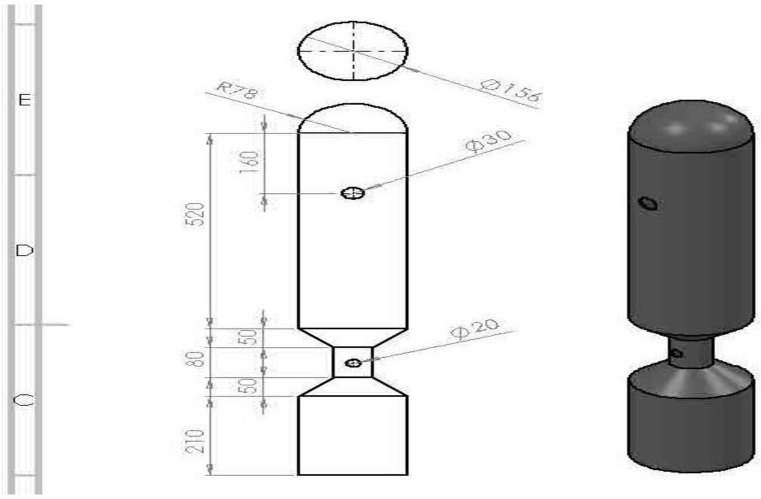


Figure A:13 Gasifier reactors part with throat

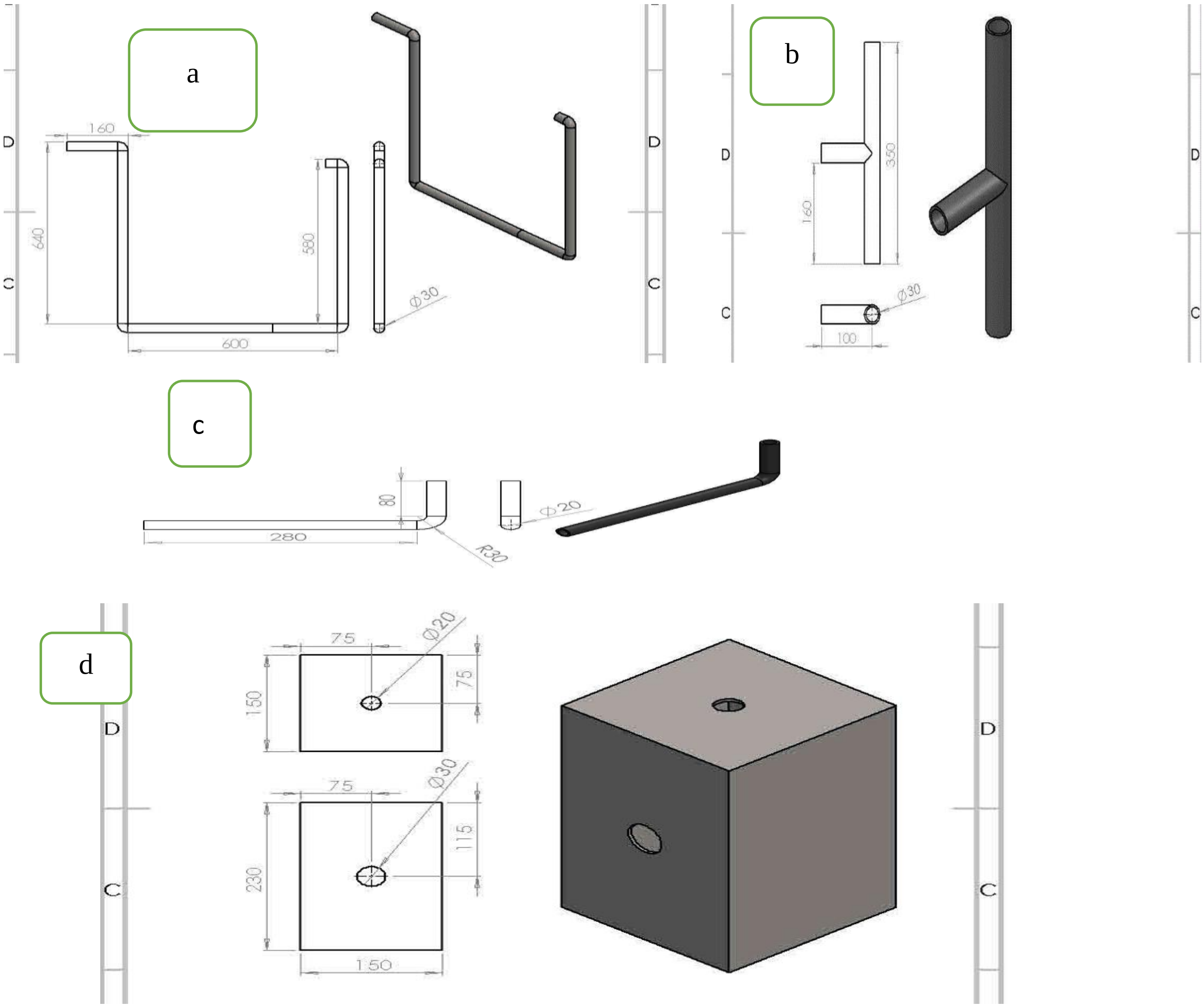
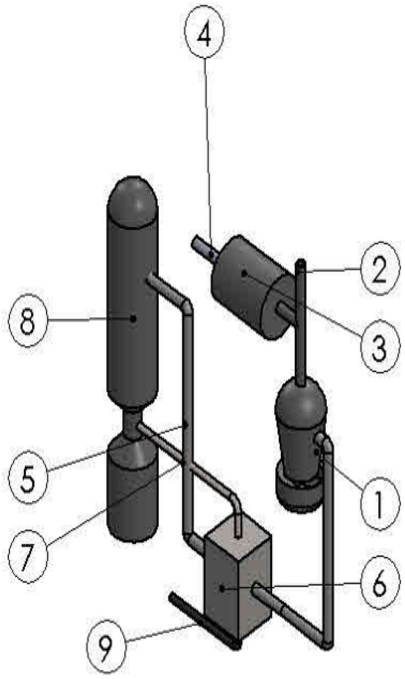


Figure A:14 Components of gasifier (a) exhaust gas pipe line, (b) Flame line, (c) Intake air pipe line, (d) Preheater



ITEM NO.	QTY.	PART NUMBER
1	1	Cyclone
2	1	Flame_Line
3	1	Suction_Fan
4	1	Fan_Outlet
5	1	Exhaust_Pipe
6	1	Preheater
7	1	Preheated_Air
8	1	Reactor
9	1	Intake_Air

Figure A:15 Assemble part of throat updraft gasifier

A.8 Code for Thermodynamic Equilibrium Model Calculation

```
% Molar mass function from periodic table
function mass = MolarMass(element)
    switch element
        case 'C'
            mass = 12.011;
        case 'H'
            mass = 1.008;
        case 'O'
            mass = 15.999;
        case 'N'
            mass = 14.007;
        case 'water'
            mass = 18.015;
        otherwise
            error('Unknown element');
    end
end
% Main script
clc; clear;
% Parameters at 1atm and 25 C
R = 8.314472; % kJ/mol-K
h_fg = 44.011; % MJ/kmol
V_m = 22.414; % Nm^3/kmol
T_gas = 1023; % K
% Fuel composition (wt%)
```

```
C = 47.93; H = 6.06; O = 43.84; N = 0.50; Other = 0.54; Ash = 3.99;
sum_comp = C + H + O + N;
C_1 = C * (100 / sum_comp);
H_1 = H * (100 / sum_comp);
O_1 = O * (100 / sum_comp);
N_1 = N * (100 / sum_comp);
Qm_fuel = 0.001255; % kg/s
ER = 0.32;
% Atom ratios
sub_H = (H_1 / MolarMass('H')) / (C_1 / MolarMass('C'));
sub_H = (O_1 / MolarMass('O')) / (C_1 / MolarMass('C'));
sub_N = (N_1 / MolarMass('N')) / (C_1 / MolarMass('C'));
M_fuel = MolarMass('C') + sub_H * MolarMass('H') + sub_O * MolarMass('O');
% Loop over moisture content
MC_list = 5:2:25;
results = [];
for MC = MC_list
    MC_frac = MC / 100;
    mu = 0.32 + 0.84 * (1 - exp(-ER / 0.229));
    % Water & air calculations
    b = (MC_frac * (12 + sub_H + 16 * sub_O)) / (18 * (1 - MC_frac));
    c_AO = ER * (1 + sub_H / 4 - sub_O / 2);
    x_N_g = sub_n / 2 + 3.76 * c_AO;
    % Solve mass balance
    syms x_1 x_2 x_3 x_4 x_5
    eq1 = x_2 + x_3 + x_5 == mu;
    eq2 = 2*b + sub_H == 2*x_1 + 2*x_4 + 4*x_5;
    eq3 = b + sub_O + 2*c_AO == x_2 + 2*x_3 + x_4;
    S = solve([eq1, eq2, eq3], [x_1, x_2, x_3, x_4, x_5]);
    x_1 = double(S.x_1);
    x_2 = double(S.x_2);
    x_3 = double(S.x_3);
    x_4 = double(S.x_4);
    x_5 = double(S.x_5);
    x_t = x_1 + x_2 + x_3 + x_4 + x_5;
    x_g = x_total + x_N_g;
    % Volume fractions
    VF_H2 = x_1 / x_g;
    VF_CO = x_2 / x_g;
    VF_CO2 = x_3 / x_g;
    VF_CH4 = x_5 / x_g;
    VF_N2 = x_N_g / x_g;
    % LHV of syngas (MJ/Nm3)
    LHV_gas = 242 * VF_H2 + 281 * VF_CO + 802 * VF_CH4; % in kJ/Nm3
    LHV_gas = LHV_gas / 1000; % in MJ/Nm3
    % Store results
    results = [results; MC, VF_CH4, VF_CO2, VF_CO, VF_H2, VF_N2, LHV_gas];
end
% Display as table
T = array2table(results, ...
```

```
    'VariableNames', {'MC', 'CH4', 'CO2', 'CO', 'H2', 'N2',
'LHV_MJ_per_Nm3'});
disp(T);
////////////////////////////////////////////////////////////////////////////////

% Define constants
R = 8.314; % kJ/mol-K - Universal gas constant
T_gas = 1023; % K - Gasification temperature


% Standard Gibbs function of formation at temperature T_gas, kJ/mol
% For CO
h_f_CO = -110.5; % kJ/mol
a_CO = 5.619e-3;
b_CO = -1.19e-5;
c_CO = 6.383e-9;
d_CO = -1.846e-12;
e_CO = -4.891e2;
f_CO = 8.684e-1;
g_CO = -6.131e-2;
DELTAg_f_T_CO = h_f_CO - a_CO * T_gas * log(T_gas) - b_CO * T_gas^2 ...
    - c_CO/2 * T_gas^3 - d_CO/3 * T_gas^4 + e_CO/(2*T_gas) + f_CO + g_CO *
T_gas;
% For CO2
h_f_CO2 = -393.5; % kJ/mol
a_CO2 = -1.942e-2;
b_CO2 = 3.122e-5;
c_CO2 = -2.248e-8;
d_CO2 = 6.946e-12;
e_CO2 = -4.891e2;
f_CO2 = 5.27;
g_CO2 = -1.207e-1;
DELTAg_f_T_CO2 = h_f_CO2 - a_CO2 * T_gas * log(T_gas) - b_CO2 * T_gas^2 ...
    - c_CO2/2 * T_gas^3 - d_CO2/3 * T_gas^4 + e_CO2/(2*T_gas) + f_CO2 +
g_CO2 * T_gas;
% For H2O
h_f_H2O = -241.8; % kJ/mol
a_H2O = -8.95e-3;
b_H2O = -3.672e-6;
c_H2O = 5.209e-9;
d_H2O = -1.478e-12;
e_H2O = 0;
f_H2O = 2.868;
g_H2O = -1.722e-2;
DELTAg_f_T_H2O = h_f_H2O - a_H2O * T_gas * log(T_gas) - b_H2O * T_gas^2 ...
    - c_H2O/2 * T_gas^3 - d_H2O/3 * T_gas^4 + e_H2O/(2*T_gas) + f_H2O +
g_H2O * T_gas;
% For CH4
h_f_CH4 = -74.8; % kJ/mol
a_CH4 = -4.62e-2;
b_CH4 = 1.13e-5;
c_CH4 = 1.319e-8;
```

```
d_CH4 = -6.647e-12;
e_CH4 = -4.891e2;
f_CH4 = 14.11;
g_CH4 = -2.234e-1;
DELTAg_f_T_CH4 = h_f_CH4 - a_CH4 * T_gas * log(T_gas) - b_CH4 * T_gas^2 ...
    - c_CH4/2 * T_gas^3 - d_CH4/3 * T_gas^4 + e_CH4/(2*T_gas) + f_CH4 +
g_CH4 * T_gas;
% Equilibrium reaction with equilibrium constants K(1) and K(2)

% Temperature range in Celsius
T_C = 350:1:1150;

% Convert to Kelvin
T_K = T_C + 273.15;
% Methane formation, endothermic reaction: C + 2H2 = CH4
DELTAG_T_K = DELTAg_f_T_CH4;
% Calculate ln(K1)
ln_K1 = (5870.53 ./ T_K) + 1.86 .* log(T_K) - 2.7e-4 .* T_K - (58200 ./ T_K.^2) - 18.007
```

```
% Water gas shift, exothermic reaction: CO + H2O = CO2 + H2
DELTAG_T_K = DELTAg_f_T_CO2 - DELTAg_f_T_CO - DELTAg_f_T_H2O;
% Calculate ln(K2)
ln_K2 = (7096.28 ./ T_K) + (-6.567) .* log(T_K) + (7.466e-3 .* T_K) ./ 2 ...
        + (-2.164e-6 .* T_K.^2) ./ 6 + (0.701e-5) ./ (2 .* T_K.^2) + 33.02;
% Convert ln(K) to K and divide by 100
K1 = exp(ln_K1) / 100;
K2 = exp(ln_K2) / 100;
% Display results
disp('Equilibrium Constants:');
disp(['K1 (Methane formation): ', num2str(K(1))]);
disp(['K2 (Water gas shift): ', num2str(K(2))]);
\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
```

```
clear; clc;
% Define temperature range
T = 300:10:2400; % Temperature range from 300 K to 2400 K
% Define phi (T/100)
phi = T / 100;
% Specific heat capacity equations (divided by 100 for kJ/(kmol·K))
Cp_CO = (69.145 - 0.7046 .* phi.^0.75 - 200.770 .* phi.^(-0.5) + 176.761 .*
phi.^(-0.75)) / 100;
Cp_CO2 = (-3.735 + 30.529 .* phi.^0.5 - 4.103 .* phi + 0.0242 .* phi.^2) /
100;
Cp_H2O = (143.050 - 183.541 .* phi.^0.25 + 82.751 .* phi.^0.5 - 3.699 .*
phi) / 100;
Cp_CH4 = (-672.870 + 439.741 .* phi.^0.25 - 24.875 .* phi.^0.75 + 323.881 .*
phi.^(-0.5)) / 100;
Cp_H2 = (56.505 - 702.740 .* phi.^(-0.75) + 1165.000 .* phi.^(-1) - 560.701
.* phi.^(-1.5)) / 100;
Cp_O2 = (37.432 + 0.0201 .* phi.^1.5 - 178.57 .* phi.^(-1.5) + 236.88 .*
phi.^(-2)) / 100;
```

```
Cp_N2 = (39.060 - 512.79 .* phi.^(-1.5) + 1072.7 .* phi.^(-2) - 820.40 .*
phi.^(-3)) / 100;
% Plot Specific Heat Capacities
figure;
hold on;
plot(T, Cp_CO, 'r', 'LineWidth', 2);
plot(T, Cp_CO2, 'g', 'LineWidth', 2);
plot(T, Cp_H2O, 'b', 'LineWidth', 2);
plot(T, Cp_CH4, 'm', 'LineWidth', 2);
plot(T, Cp_H2, 'c', 'LineWidth', 2);
plot(T, Cp_O2, 'k', 'LineWidth', 2);
plot(T, Cp_N2, 'y', 'LineWidth', 2);
hold off;
% Formatting the plot
xlabel('Temperature (K)');
ylabel('Specific Heat Capacity (kJ/(kmol·K))');
title('Specific Heat Capacities of Gases vs Temperature');
legend('CO', 'CO₂', 'H₂O', 'CH₄', 'H₂', 'O₂', 'N₂', 'Location',
'NorthWest');
grid on;
```

\\

```
%% --- Constants ---
R = 8.314;                  % Universal gas constant, kJ/kmol.K
T_a = 298.15;               % Ambient temperature, K
%% --- Standard chemical exergies of components (kJ/kmol) ---
e0_H2  = 238490;
e0_CO  = 275430;
e0_CO2 = 20140;
e0_H2O = 11710;
e0_CH4 = 836510;
e0_N2  = 720;
%% --- Input mole fractions of producer gas components ---
% x_H2 = 0.15;
% x_CO = 0.20;
% x_CO2 = 0.10;
% x_H2O = 0.05;
% x_CH4 = 0.05;
% x_N2 = 0.45;
%% --- Chemical Exergy of each component (kJ/kmol) ---
exe_chem_H2  = (e0_H2  + R * T_a * log(x_H2))  * x_H2;
exe_chem_CO  = (e0_CO  + R * T_a * log(x_CO))  * x_CO;
exe_chem_CO2 = (e0_CO2 + R * T_a * log(x_CO2)) * x_CO2;
exe_chem_H2O = (e0_H2O + R * T_a * log(x_H2O)) * x_H2O;
exe_chem_CH4 = (e0_CH4 + R * T_a * log(x_CH4)) * x_CH4;
exe_chem_N2  = (e0_N2  + R * T_a * log(x_N2))  * x_N2;
%% --- Total chemical exergy of gas (kJ/kmol) ---
exe_chem_gas = exe_chem_H2 + exe_chem_CO + exe_chem_CO2 + exe_chem_H2O +
exe_chem_CH4 + exe_chem_N2;
%% --- Define physical exergy data ---
% Example: You must define these variables before running
```

```
% h_T_1 = ...; h_0_1 = ...; S_T_1 = ...; S_0_1 = ...; etc.
exe_phy_CO  = (h_T_1 - h_0_1 - T_a * (S_T_1 - S_0_1)) * x_CO;
exe_phy_CO2 = (h_T_2 - h_0_2 - T_a * (S_T_2 - S_0_2)) * x_CO2;
exe_phy_CH4 = (h_T_3 - h_0_3 - T_a * (S_T_3 - S_0_3)) * x_CH4;
exe_phy_H2  = (h_T_4 - h_0_4 - T_a * (S_T_4 - S_0_4)) * x_H2;
exe_phy_N2  = (h_T_5 - h_0_5 - T_a * (S_T_5 - S_0_5)) * x_N2;
exe_phy_H2O = (h_T_6 - h_0_6 - T_a * (S_T_6 - S_0_6)) * x_H2O;
%% --- Total physical exergy (kJ/kmol) ---
exe_phy_gas = exe_phy_H2 + exe_phy_CO + exe_phy_CO2 + exe_phy_H2O +
exe_phy_CH4 + exe_phy_N2;
%% --- Total gas exergy (chemical + physical) ---
exe_gas = exe_chy_gas + exe_phy_gas;
%% --- Biomass chemical exergy (fuel) ---
% Example composition ratios (you must define):
% sub_H = 1.526; % H/C
% sub_O = 0.652; % O/C
% sub_N = 0.0113; % N/C
xj = (1.044 + 0.016 * sub_H - 0.3493 * sub_O * (1 + 0.0531 * sub_H) + 0.0493
* sub_N) / ...
     (1 - 0.4124 * sub_O);
exe_chem_fuelmass = xj * LHV_biomass * 1e3;     % kJ/kg
exe_chem_fuel = exe_chem_fuelmass * M_fuel;       % kJ/kmol
```

```
%% --- Exergy efficiency ---
% Define: x_t (syngas yield or conversion factor, e.g. moles syngas/mole
biomass)
% x_t = 1; % Example
Eta_exe_chem = x_t * exe_gas / exe_chem_fuel;
%% --- Irreversibility ---
I = 1 - Eta_exe_chem;
%% --- Display results ---
fprintf('Exergy efficiency: %.4f\n', Eta_exe_chem);
fprintf('Irreversibility (I): %.4f\n', I);
fprintf('Chemical exergy of gas: %.2f kJ/kmol\n', exe_chem_gas);
fprintf('Physical exergy of gas: %.2f kJ/kmol\n', exe_phy_gas);
fprintf('Total gas exergy: %.2f kJ/kmol\n', exe_gas);
fprintf('Chemical exergy of fuel: %.2f kJ/kmol\n', exe_chem_fuel);
```