Ethiopian Institute of Technology – Mekelle (EiT –M)

MSc Thesis

On

OPTIMIZING BIOMASS COMBUSTION IN INDUSTRIAL BURNERS: A CASE STUDY ON MASS AND ENERGY BALANCE AT MAICHEW PARTICLE BOARD FACTORY

A Thesis Submitted to the school of Mechanical and Industrial Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Energy Technology

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December, 2024

Mekelle, Ethiopia

DECLARATION

I hereby declare that this thesis is the original research work of the author, conducted under the supervision and guidance of the advisor. Except for specific notes and acknowledgments cited in the text, the thesis does not include any research results published or written by others, nor does it contain material submitted for any degree or certificate at Mekelle University or any other institution. In this thesis, I have clearly acknowledged and expressed my gratitude to those who have contributed to this study.

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ACKNOWLEDGEMENT

First and foremost, I would like to thank the Almighty Lord for giving me the strength to complete this work and realize my aspirations. I wish to express my deep gratitude to my advisor, Dr. Mulualem Gebregergis, and my co-advisor, Angesom Gebreegzabiher (PhD candidate), for their encouragement, constructive feedback, and helpful comments.

My special thanks go to my mother, Tsire Kidanu, and my brothers, Dr. Yonas Weldemariam and Assefa Weldu, as well as my beloved son, Naod, for their unwavering moral support throughout my studies. I would also like to acknowledge my niece, Liwam Weldeabrha, and my friend, Meaza Abrha, who have always stood by me and played an important role in the completion of my work.

Last but not least, I extend my heartfelt thanks to all the technicians and engineers at Maichew Particle Board Factory, as well as my beloved family members, who have been a constant source of support throughout my academic journey.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

1. E_a = Heat input of combustion air
2. H_a = Enthalpy of combustion air
3. T_{ref} = Reference temperature
4. M_R = Mass rate of air
5. E_{wd} = Energy input rate of fuel (wood)
6. MR_{wd} = Mass rate of wood

7. HHV= Higher heating value
8. E_{unbC} = Rate of energy loss to unburned carbon
9. MR_{unbc} = Mass rate of unburned carbon
10. E_{los} CO= Energy lost due to formation of carbon mono oxide
11. MRCC0 = Mass rate of carbon burned to CO
12. MWC0= Molecular weight of CO
13. T F= Temperature of flue gas
14. T_{amb} = Ambient temperature
15. XH= Mass fraction of hydrogen in fuel
16. XC= Mass fraction of carbon
17. XS= Mass fraction of Sulphur
18. XO= Mass fraction of oxygen
19. XN= Mass fraction of nitrogen
20. MRA= Mass rate of air
21. MRC_{wd}= Mass rate of carbon in wood
22. MRO_{wd}= Mass rate of oxygen in wood
23. $MRH_{2\ wd}$= Mass rate of hydrogen in wood
24. MRN_{2wd}= Mass rate of nitrogen in wood
25. MR_{wdin}= Total mass rate of wood to combustor
26. M_{H2O}= Molecular weight of water
27. MC_{wd}= Moisture content of wood
28. MR_{fg}= Mass rate of flue gases

29. C_{Pa}= Specific heat capacity of air

30. MR_{ath}= Theoretical mass of air

31. AF = Actual air-fuel ratio

32. LHV=Lower heating value

33. EL_{ash}= Energy loses in ash

34. ELR= Energy loses with

ABSTRACT

The growing need to reduce reliance on fossil fuels has prompted exploration of biomass as a sustainable energy source. Maichew Particle Board Factory, a sister company of EFFORT, producing 3,360 tons of sawdust annually, has untapped potential to utilize biomass for energy generation. This study aims to perform a mass and energy balance analysis on the factory's burner, optimize the air-to-fuel ratio, and identify challenges in transitioning to biomass as the primary fuel. A combustion analysis was conducted using the fuel combustion equation, and optimization of the air-to-fuel ratio was carried out using Microsoft Excel Solver.

The analysis revealed that the burner consumes 376.95 kg of sawdust per hour and 6,180.9 kg of air per hour, producing 5,791.5 MJ/hr of flue gas energy for the dryer.

The findings underscore the factory's capacity to utilize sawdust effectively as fuel, offering a pathway to reduce fossil fuel dependence and enhance energy efficiency in biomass-based operations.

KEY WORDS*: Bio mass, Bio fuel, Maichew, Mass, Energy, Sawdust*

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the study

Bioenergy is a renewable energy source derived from living organisms, such as plants and animals, and their byproducts. This includes plant residues, human waste, animal dung, agricultural waste, crop residues, forestry resources, fuelwood, municipal solid waste, and sewage sludge. Among these, sawdust a byproduct of the sawmilling industry is often regarded as timber-industrial waste. If not properly managed, it can contribute to significant environmental pollution. However, sawdust has great potential to be transformed into a valuable fuel source, either by burning it directly or converting it into fuel gas, contributing to sustainable energy production [1, 2].

A. Global Context

Globally, biomass energy has become a significant component of the renewable energy mix. According to the International Energy Agency (IEA), biomass provides approximately 10% of the global energy supply, with its share expected to grow as countries strive to meet ambitious decarbonization goals. Best practices in biomass combustion have emerged across the world, focusing on reducing emissions, improving combustion efficiency, and promoting waste-to-energy (WtE) solutions. Countries like Sweden and Finland lead in biomass utilization, converting forestry residues into heat and power through advanced combustion systems. [3,5]

Waste-to-energy policies are playing a pivotal role in fostering the adoption of biomass energy. Many nations, including those in the European Union, have implemented strict regulations on waste disposal, incentivizing industries to turn organic waste into energy. Advanced biomass combustion technologies, such as fluidized bed combustion and gasification, are becoming standard practice for improving energy efficiency and reducing environmental impact. [3,4]

B. National and Regional Context

In Ethiopia, biomass remains the dominant energy source, contributing to over 90% of the total energy consumption. Traditional biomass, including fuelwood and agricultural residues, is primarily used for household cooking and heating. However, the transition to modern biomass energy systems has been slow due to technological, economic, and policy challenges. The country has significant potential for biomass energy generation, particularly through sawdust, agricultural waste, and municipal solid waste. Policies such as Ethiopia's National Energy Policy emphasize renewable energy development, including biomass, to reduce reliance on imported fossil fuels and mitigate environmental degradation. [1,2]

Regionally, the Tigray region, where the Maichew Particle Board Factory is located, produces substantial amounts of forestry and sawmill byproducts. Despite the availability of sawdust, its utilization remains limited, with much of it discarded as waste. Transforming this byproduct into a primary energy source aligns with Ethiopia's sustainable development goals and offers opportunities for industrial efficiency and environmental benefits. [1,2,9]

C. Challenges and Opportunities

The adoption of biomass energy faces several challenges, including the lack of efficient combustion technologies, limited awareness of biomass energy benefits, and insufficient infrastructure for waste collection and processing. Furthermore, technical issues such as the high moisture content and varying particle sizes of biomass complicate its combustion process. [6, 7]

However, these challenges are accompanied by significant opportunities. The shift toward renewable energy sources, supported by global climate policies, provides an impetus for biomass energy development. Technological advancements in combustion systems, such as co-firing and fluidized bed burners, enable industries to utilize biomass efficiently. Locally, industries like the Maichew Particle Board Factory can capitalize on these opportunities to optimize their energy usage, reduce costs, and contribute to a circular economy by reusing waste products. [6,8]

This thesis investigates the mass and energy balance of a burner utilizing a high biomass ratio to supply heat to the factory’s dryer. Currently, the factory employs a co-firing system where fossil fuels are the primary energy source, supplemented by sawdust. The study aims to optimize the air-to-fuel ratio for improved combustion efficiency while recommending a dedicated biomass burner for enhanced energy production.

The research provides critical insights into the potential of sawdust combustion as an efficient and sustainable energy solution. By determining the optimal air-to-fuel ratio and analyzing the energy released from the fuel, the study supports achieving higher efficiency and cleaner energy production. This aligns with global efforts to transition from fossil fuels to renewable energy sources, contributing to Ethiopia’s energy sustainability and environmental goals.

1.2 Statement of the problem

Fossil fuel resources are diminishing, while global energy demand continues to rise. Therefore, transitioning from non-renewable to renewable energy sources is essential for sustainable development in any country. Maichew Particle Board Factory, which consumes large amounts of fossil fuels (diesel and heavy oil) to dry its raw material (flakes used in particle boards), faces similar challenges. The factory produces significant quantities of byproducts, such as eucalyptus leaves, branches, and saw dust, which are discarded due to vehicles.

The Maichew particle board factory uses sawdust as a supplementary fuel alongside heavy oil in its burner. Despite the higher heat release rate of sawdust, the system encounters significant operational challenges due to improper adjustment of the burner's parameters for dual fuel usage. Frequent blockages occur in the fuel handling system, caused by the accumulation of larger biomass particles and ash residues that the current configuration cannot efficiently process. Inconsistent combustion efficiency leads to incomplete combustion, reducing energy output, causing uneven heat distribution, and affecting the temperature profile critical for drying and manufacturing processes. Moreover, increased emissions of partially burned gases, such as carbon monoxide and unburned hydrocarbons, signal suboptimal combustion conditions, posing environmental and health risks.

Additionally, the inability to maintain a stable air-to-fuel ratio results in energy imbalance, inefficient fuel utilization, and higher operating expenses. Frequent operational interruptions due to blockages and equipment malfunctions further disrupt production schedules. Addressing these challenges requires recalibrating burner parameters to match the combustion characteristics of sawdust and implementing systems to maximize sawdust fuel usage ; thereby improving combustion efficiency and system reliability.

1.3 Objectives of the research

1.3.1 General objective

This research work is aimed to optimized biomass combustion of industirial burner by performing mass and energy balance of burner.

1.3.2 Specific objectives

1. To calculate the heat required by the dryer
2. To determine the amount of flue gas and the mass of fuel required in the burner
3. Optimizing air fuel ratio
4. To identify cofiring technical challenges

1.4 Scope of the Study

This study focuses on evaluating and optimizing energy consumption in the drying and combustion processes involved in biomass co-firing at Maichew Particle Board Factory. It includes a detailed mass and energy balance analysis of the dryer system to determine the precise heat required for the drying process and to calculate the corresponding flue gas flow rate. Additionally, a comprehensive mass and energy balance will be conducted on the burner system to evaluate its heat output relative to the dryer’s requirements. The optimization of the air-to-fuel ratio will ensure efficient combustion and minimize fuel consumption, taking into account the specific properties of sawdust as the primary biomass fuel.

The study also identifies and evaluates technical challenges to biomass co-firing, focusing on theoretical analysis and data collection related to optimizing the use of sawdust as a fuel source. Furthermore, a situational analysis will be carried out to determine the optimal ratio of sawdust to traditional fuel, enhancing the efficiency and sustainability of the combustion process. This research is limited to theoretical modeling, data collection, and analysis, and does not extend to experimental implementation or the evaluation of alternative energy systems beyond biomass co-firing.

CHAPTER TWO

2. REVIEW OF LITERATURES

2.1 Energy from Biomass Fuel

Biomass fuel has emerged as a key alternative to traditional fossil fuels, offering renewable and sustainable energy solutions in the context of growing global energy demands and environmental concerns. Biomass energy refers to the energy derived from organic materials, including plant residues, wood, agricultural waste, and animal byproducts. This literature review explores the historical development, types of biomass fuel, energy conversion processes, challenges, and future prospects of biomass as an energy source. [8, 9]

The use of biomass as a fuel is one of humanity's oldest energy sources, predating the use of fossil fuels. Historically, wood was burned for heating and cooking. However, the modern use of biomass for energy production has evolved with advances in technology, allowing for more efficient energy conversion. The oil crises of the 1970s sparked renewed interest in biomass as a potential alternative to fossil fuels, which has continued to grow in the context of climate change and energy security concerns. [9] Biomass fuel can be categorized into several types based on the source material:

- **Wood and Woody Biomass**: This includes firewood, wood chips, sawdust, and other forestry residues.
- **Agricultural Residues**: These include crop waste such as straw, husks, and corn stalks.
- **Animal Waste**: Manure from livestock can be used for bioenergy, particularly in biogas production.
- **Municipal Solid Waste (MSW)**: Organic waste from urban environments can be converted to energy.
- **Energy Crops**: Specific crops like switchgrass, miscanthus, and fast-growing trees are cultivated for biomass production. [8, 9, 10]

2.1.3. Energy Conversion Processes

The conversion of biomass to energy can occur through several processes, broadly categorized into **thermochemical**, **biochemical**, and **mechanical** methods.

A. **Thermochemical Conversion**:

Includes combustion, gasification, and pyrolysis. Combustion is the direct burning of biomass to produce heat or electricity. Gasification converts biomass into syngas (a mixture of hydrogen and carbon monoxide), which can then be used for power generation. Pyrolysis involves heating biomass in the absence of oxygen, producing bio-oil, syngas, and biochar. [10]

B. **Biochemical Conversion**:

Includes anaerobic digestion and fermentation. Anaerobic digestion breaks down organic matter in the absence of oxygen to produce biogas (methane and carbon dioxide). Fermentation is used to produce bioethanol, particularly from sugar-rich or starch-based biomass like corn or sugarcane. [9, 11]

C. **Mechanical Conversion**:

Mechanical processes, such as pressing, can be used to extract bio-oil from crops like soybeans or palm oil, which can then be refined into biodiesel.

Thermochemical processes, particularly gasification and pyrolysis, are gaining popularity due to their ability to convert a wide range of biomass types into clean energy forms with relatively high efficiency. [12]

Biomass energy has several environmental benefits, including its potential to reduce greenhouse gas (GHG) emissions. Unlike fossil fuels, which release carbon that has been stored underground for millions of years, biomass fuels emit carbon that was recently absorbed by plants, making the process carbon-neutral when managed sustainably. Biomass can also reduce waste by utilizing agricultural residues, municipal waste, and other organic materials that would otherwise contribute to landfills. [13]

Economically, biomass energy can provide energy security by reducing dependence on imported fossil fuels, especially for rural and developing areas. It can also create jobs in biomass cultivation, processing, and technology development [12, 13]

Table 1. Major categories and types of biomass fuel

Wood processing residue	**Grown biomass**	**Urban wood residues**	**Agriculture residues**	**In-forest residues**
-Sawdust and paper trash -Tree pruning's and yard clippings	-Switchgrass -Hybrid poplars	-Construction and demolition wood - Wood and brush -Wood waste	-Corn Stover -Rice straw and wheat straw -Use vegetable oils	-Clearance wood -Dead/doomed trees -Excess timber

2.1.1 Sawdust biomass

Sawdust biomass refers to the use of sawdust—a byproduct of wood processing—as a renewable energy source. Sawdust is a fine powdery material produced during activities such as sawing, milling, and sanding wood. It is considered a form of biomass because it is derived from organic, carbon-based material, specifically wood. [10, 13]

Key Features of Sawdust Biomass:

A. **Abundant Byproduct**: Sawdust is commonly produced in large quantities in industries such as sawmills, furniture manufacturing, and construction. Instead of being discarded as waste, sawdust can be repurposed for energy production. [14]

B. **Renewable Energy Source**: Since sawdust comes from trees, which can be replanted and regrown, it is classified as a renewable source of energy. This makes it an environmentally friendly alternative to fossil fuels. [14, 15]

2.2 Saw Dust Potential of Ethiopia

There are approximately 39 sawmills and 5 to 10 factories producing plywood in Ethiopia, along with 200 to 300 joinery and furniture factories operating across the country. Most of the sawmills are concentrated in the southern and southwestern regions. However, the total number of sawmills and their log intake capacities are relatively low, averaging around 3,500 cubic meters per year per shift. Due to limited availability of wood logs, many mills operate below their nominal capacity. [15]

Sawdust from distant sawmills across the country is often piled up or discarded, left to decay due to its lack of economic value. In the Oromia region, the average annual volume of wood processed in these mills ranges from 1,000 to 3,500 cubic meters. According to a survey, about 4,600 tons of sawdust residue could be produced annually from four sawmills in the region. Despite their distance from major towns, some sawmills may be of interest due to the significant amounts of residue they have accumulated, as they lack alternative uses. [16]

At Maichew Particle Board Factory, the sawdust generated as a byproduct of production totals around 3,360 metric tons annually [2]. This waste can be transformed into a valuable product, reducing the cost of disposal and providing economic benefits. [14-16]

For years, the plant did not repurpose the sawdust into a profitable product or utilize it as fuel for boilers or burners. Although the factory has recently begun using sawdust as an additional fuel, the operators are still unaware of the exact quantities being consumed.

2.3 Fuel for Combustion

Combustion of fuels occurs when the fuel reacts with an oxidant. The process of burning biomass, however, is not yet fully understood or easily expressed in mathematical terms. This complexity arises from the heterogeneity of wood and the intricate mass and heat transfer mechanisms that occur during combustion, along with multiple chemical reactions. Therefore, understanding the characteristics of biomass particles is crucial for improving combustion processes. [16]

The characteristics of biomass particles vary depending on the source and type of biomass, but several key properties influence their behavior in energy production processes such as combustion, gasification, or pyrolysis. These properties determine the efficiency, handling, and overall performance of biomass as a fuel. Below are the main characteristics of biomass particles. [17, 18]

I. Physical Properties

A. **Particle Size and Shape**: Biomass particles can range from fine powders (like sawdust) to larger chunks (wood chips or pellets). Particle size and shape affect the combustion rate, drying time, and ease of transportation and storage. Smaller particles typically burn faster due to their larger surface area relative to volume, while larger particles require more time to fully combust. [16]

B. **Bulk Density**: The bulk density of biomass refers to the mass per unit volume, including void spaces between particles. It influences the fuel handling, storage, and transportation costs. Low-density biomass like straw or leaves may require densification (e.g., into pellets or briquettes) to improve these factors. [18]

C. **Moisture Content**: Biomass often contains significant moisture, which impacts its energy content. High moisture content reduces the calorific value (energy content) of the biomass and requires additional energy for drying before combustion or gasification can occur efficiently. Typical moisture content ranges from 10% to 60%, with an ideal level below 15% for most combustion processes. [14, 20]

II. Chemical Composition

A. **Elemental Composition**: Biomass typically contains carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and trace amounts of sulfur (S) and chlorine (Cl). The elemental makeup determines the energy content of the biomass and its emissions. A typical biomass composition might be around 45–50% carbon, 5–6% hydrogen, and 40–45% oxygen. The presence of nitrogen, sulfur, and chlorine can lead to the formation of pollutants like nitrogen oxides (NOx), sulfur dioxide (SO2), and hydrochloric acid (HCl) during combustion. [19-21]

B. **Ash Content**: The ash content is the inorganic residue left after biomass combustion, typically composed of minerals such as silica, calcium, potassium, and magnesium. Low ash content is preferable for energy production, as high ash levels can lead to slagging, fouling, and corrosion in combustion equipment. Biomass types like wood have lower ash content compared to agricultural residues like straw. [22]

C. **Volatile Matter**: Biomass has a high volatile matter content, typically between 70% and 85%, meaning that a significant portion of the material vaporizes upon heating. This is advantageous in combustion and gasification processes as it allows for rapid ignition and flame propagation. [21, 25]

III. Thermal Properties

A. **Calorific Value**: The calorific value (or heating value) of biomass refers to the amount of energy released during combustion. It is typically measured in megajoules per kilogram (MJ/kg). Biomass calorific values range between 15 MJ/kg and 20 MJ/kg for dry materials. Woody biomass generally has a higher calorific value than agricultural residues. [22]

B. **Thermal Decomposition**: Biomass undergoes thermal decomposition when heated in the absence of oxygen (as in pyrolysis or gasification). The rate of decomposition and the yield of bio-oil, syngas, or biochar depend on the composition and structure of the biomass. [21, 22]

IV. Mechanical Properties

A. **Hardness and Grindability**: These properties affect how easily the biomass can be processed into smaller particles for combustion or gasification. Softer materials like agricultural residues are easier to grind, while harder materials like woody biomass may require more energy to process. [23]

B. **Tensile Strength and Durability**: These properties determine how well biomass particles can withstand mechanical stresses during transportation and handling. For example, pellets or briquettes need sufficient durability to prevent breakage during shipping. [24]

V. Ash Melting Point

The ash melting point of biomass is the temperature at which ash softens and starts to melt. Low ash melting points can cause slagging and fouling in combustion systems. Biomass types like straw, which have higher potassium content, tend to have lower ash melting points, leading to operational challenges in boilers and furnaces. [23]

VI. Biodegradability

Biomass particles are biodegradable, meaning they break down over time due to microbial activity. While this is an advantage in terms of environmental impact, it can be a challenge for long-term storage, as biodegradation reduces the fuel quality and energy content of the biomass.

[23, 26]

VII. Energy Density

Energy density refers to the amount of energy stored per unit volume of biomass. Woody biomass and densified forms such as pellets have higher energy densities than loose agricultural residues, making them more efficient to transport and store. [26]

VIII. Combustion Characteristics

A. **Ignition Temperature**: Biomass typically has a lower ignition temperature compared to coal, which makes it easier to ignite. The ignition temperature of biomass can range from 250°C to 400°C, depending on the type.

B. **Burning Rate**: Biomass generally burns faster than coal due to its high volatile content. This can be beneficial for quick energy generation but requires careful control in combustion systems to maintain stable temperatures and avoid inefficiencies. [27]

2.4 Co-firing

Co-firing refers to the simultaneous combustion of two or more types of fuels in a single furnace or boiler. It is a promising technology for utilizing renewable energy sources, reducing greenhouse gas emissions, and improving the overall efficiency of energy production systems. Co-firing is particularly relevant in the context of biomass and fossil fuels, where biomass is used as a supplementary fuel alongside traditional fossil fuels like coal or natural gas. [22, 25, 28]

2.4.1 Benefits of Co-firing

- **Reduction of Greenhouse Gas Emissions**: Co-firing biomass with fossil fuels can significantly reduce CO_2 emissions since biomass is considered carbon-neutral over its lifecycle. The carbon dioxide released during combustion is approximately equal to the amount absorbed by the biomass during its growth. [30]
- **Utilization of Waste Materials**: Co-firing can utilize agricultural residues, wood waste, and other forms of biomass that might otherwise be discarded, thereby reducing waste and promoting a circular economy. [30]
- **Energy Diversification**: Co-firing allows for a more diverse energy mix, enhancing energy security by reducing reliance on a single fuel source. It can also help stabilize energy prices. [27]
- **Improved Boiler Efficiency**: Some studies have indicated that co-firing can

enhance the thermal efficiency of boilers compared to burning fossil fuels alone. The presence of biomass can improve combustion characteristics and reduce fouling and corrosion issues associated with high-sulfur fuels. [24]

2.4.2 Co-firing Technologies

Co-firing technology is now a time the most competitive option to exploit greatest benefit energy from both fuels. It is used to produces both electricity and heat energy. Co-firing technologies can be classified as followings:

I. Types of Co-firing

A. Direct Co-firing

Direct co-firing involves the simultaneous combustion of biomass and fossil fuels within the same boiler or furnace. This method is the most straightforward and widely adopted technology for co-firing biomass. However, various technical challenges can arise depending on the type of boiler used, as all constituents of the biomass enter the fuel system. [33]

Direct co-firing can be applied in several types of boilers, including cyclone, fluidized bed combustion (FBC), & pulverized coal combustion (PCC) boilers. A survey of biomass co-firing practices in Europe found that the proportion of biomass co-fired in stoker boilers ranged from 20% to 90%, in FBC boilers from 20% to 90%, and in PCC boilers from 3% to 20%. This indicates that stoker and FBC boilers, which are designed to fully accommodate biomass, are significantly better suited for high percentages of biomass co-firing compared to PCC boilers.

In direct co-firing, biomass is introduced directly into the coal-burning boiler. This can be accomplished through one of four basic methods, depending on how the biomass is blended with the primary fuel and how it is injected into the boiler. These methods are described below: [35]

- **Co-Pulverizing**: Both biomass and coal are ground together before being fed into the boiler.
- **Separate Pulverizing, Common Injection**: Biomass and coal are pulverized

separately but injected into the boiler at the same point.

- **Separate Pulverizing, Separate Combustion**: Biomass and coal are pulverized and combusted separately, each in its designated area of the boiler.
- **Separate Pulverizing with Common Injection**: Similar to the second method, but the biomass and coal are injected at different points within the boiler.

Each of these options has its own implications for combustion efficiency, emissions control, and overall system performance. [36]

2.5 Barriers for sawdust maximization combustion

Maximizing the combustion of sawdust as a biomass fuel presents several barriers that can hinder its effective use in energy production. Understanding these barriers is crucial for developing strategies to overcome them and enhance the utilization of sawdust as a renewable energy source. Here are some of the primary challenges: [37]

2.5.1 Technical and equipment limitations

I. Characteristics of fuel

The physical and chemical properties of biomass, including its chemical composition and thermal characteristics, significantly influence its combustion efficiency. Key attributes defining biomass fuel characteristics are outlined below.

A. Heating Value

The heating value is a crucial property of any fuel, representing the amount of energy released during the complete combustion of the fuel at a reference temperature and pressure. It is categorized into two types:

Higher Heating Value (HHV): This is the experimentally determined value of heat released during combustion per unit weight of the fuel, where the water formed during combustion is in the liquid phase. Therefore, the heat of vaporization for this water is not subtracted from the heating value.

Lower Heating Value (LHV): Similar to HHV, but in this case, it is assumed that the water produced during combustion remains in vapor form. Consequently, the heat of vaporization is accounted for, leading to a lower heating value.

B. Moisture Content

The moisture content of green wood poses several challenges to efficient combustion:

- **Increased Flue Gas Volume**: High moisture content increases the volume of flue gas generated during combustion, necessitating greater draft fan output.
- **Reduced Boiler Efficiency**: Moisture absorbs heat from the combustion process, diminishing overall boiler efficiency.
- **Clumping of Fines**: High moisture levels can cause fine particles in the fuel to clump together, forming larger aggregates that impair the flowability of the fuel.

Moisture content on a wet (or green) basis is defined as the ratio of the weight of water present in the wood to the total weight of the wood plus water:

M.C. (wd) = Weight of water in wood /Weight of dry wood +weight of water in the wood

II. Effect of Particle Size and Shape

The size and shape of biomass particles significantly affect the combustion process. Larger particles may take longer to burn completely, potentially leading to unburned fuel that flows into the ash pit. Conversely, fine particles have an increased likelihood of bridging, particularly in materials with higher aspect ratios, such as mulch-like or tub-ground material. [38]

The appropriate size and shape of wood particles must be considered prior to combustion to ensure efficient conveyance and burning. Biomass particle sizes can vary widely, ranging from 1/100 inch for fine sawdust to 6 inches for coarse hogged bark. Although sawdust has a higher heat release rate, its particle size can impact both the combustion process and the performance of fuel handling machinery. [39]

III. Effect of Excess Air

To prevent incomplete combustion, it is necessary to supply excess air beyond the stoichiometric amount required in the combustion system. Excess air levels can range from 0% to over 200%, depending on the type of combustion system employed.

While increasing excess air can enhance flue gas volume flow rate, it can also reduce residence time, leading to increased particulate carryover and unburned carbon, thereby diminishing combustion efficiency and increasing emissions. Additionally, higher excess air can raise pressure drops through the combustor, resulting in higher power consumption. The temperature of the air and its introduction location into the furnace also play critical roles in the combustion process. Excess air can lower flame and furnace temperatures, subsequently reducing the rate of combustion. [39, 41]

IV. Size of the Burner

Biomass typically contains about 70% volatile matter, resulting in a larger volume of flue gases per unit of energy compared to coal. This can alter the flow patterns of combustion gases through the boiler and limit the proportion of biomass that can be co-fired in existing installations.

The co-firing of biomass, particularly wet biomass, may influence the maximum achievable boiler load and boiler efficiency, depending on mill constraints. When co-firing low ratios of dry biomass (<10% moisture content), constraints are minimal. Generally, the absence of large biomass particles (>2-5 mm) passing to the burners, coupled with acceptable combustion behavior of the blended fuel, promotes efficiency. Biomass materials tend to be more reactive during combustion than most coals, and the unburned carbon levels in bottom and fly ashes are typically similar to or lower than those observed when firing coal alone. [40]

Incorporating biomass into a coal-fired boiler usually does not significantly affect overall boiler efficiency; at worst, it may result in a slight decrease in efficiency. However, at higher co-firing percentages, issues related to ash become critical. Research by Jaap Kiel highlights challenges associated with ash deposition in the near-burner zone, which can adversely affect co-firing efficiency and combustion conditions, potentially leading to increased unburned carbon levels in the ash. [41]

2.5.2 Formation of chemicals during combustion

I. Deposit Formation and Ash Deposition

The combustion of biomass can lead to significant deposit formation, particularly due to the alkali content found in some biomass fuels, combined with the notably lower melting point of biomass ash. This issue manifests as two primary phenomena: slagging and fouling.

Slagging refers to the accumulation of ash on heat transfer surfaces and refractory linings in the furnace that are primarily exposed to radiant heat. Fouling, on the other hand, occurs in the heat recovery section of the steam generator, where fly ash deposits form due to convective heat exchange when the ash remains unquenched at temperatures below its melting point. [41]

A related process is sintering, which involves the fusion of deposit particles into a more compact form. The extent of deposit formation, including both fouling and slagging, can vary significantly throughout the boiler based on local gas temperatures and tube conditions.

The ash produced from biomass combustion often contains substantial amounts of potassium, phosphate, and calcium—elements that contribute to the formation of ashes with lower melting points. These low-melting-point ashes can create sticky layers that lead to bed agglomeration and de-fluidization in fluidized bed combustion systems. This agglomeration increases local temperatures, which can further accelerate the process, potentially resulting in a fully sintered bed characterized by a glassy phase that binds the bed particles together. To mitigate such issues, it is recommended that biomass be processed in dry ash gasification systems, where operational temperatures typically reach up to 950-1000ºC. Exceeding these temperatures may cause ash fusion and chemical agglomeration problems. [35, 39, 41]

Erosion is defined as the progressive loss of material from a solid surface due to mechanical interactions between that surface and a fluid or solid particles carried by the gas or fluid at significant velocities. Several types of erosion are relevant to the co-firing of biomass with coal, with solid particle erosion and erosion/corrosion being particularly noteworthy. Solid particle erosion occurs due to the repeated impact of small solid particles in a gaseous medium, leading to material loss. Erosion/corrosion refers to the simultaneous damage caused by mechanical erosion and electrochemical corrosion, which often interact and exacerbate each other's effects, resulting in compounded damage. [12, 43]

Fluidized bed combustion systems are especially susceptible to solid particle erosion due to the movement of bed material particles. While erosion is also present in single coal combustion plants, the relationship between erosion and biomass co-firing is not well-defined. However, the synergy between erosion and corrosion, along with the potentially higher corrosive nature of certain biomass types (especially those with high chlorine content), could pose significant challenges in some co-firing systems. [42, 44]

The presence of chlorine in biomass can lead to corrosion issues during co-firing. Interestingly, some mitigation of chlorine-induced corrosion can occur through reactions between sulfur from coal and alkali compounds from biomass. This interaction may produce alkali chlorides that condense from biomass-based flue gases, reacting with SO_2 (predominantly from coal) to form less corrosive alkali sulfates.

However, this mitigating effect does not occur under reducing conditions, and in oxidizing conditions, it can be inhibited by lower temperatures, which reduce the kinetic rates of sulfate formation. Additionally, since biomass is often injected into only a few burners, and many boilers do not effectively mix flue gases in their furnace sections, the resulting gas compositions near the boiler exit can vary significantly between burners. This variability may affect the ameliorating effects of sulfur from coal on the flue gases derived from biomass. [33, 37, 43]

Corrosion during co-firing can substantially impact the lifespan of the affected equipment, resulting in increased financial and operational costs. Research indicates that employing suitable materials and additives can help mitigate corrosion in boilers burning biomass, even at temperatures as high as 550°C. One effective additive is ammonium sulfate, which can convert gaseous potassium chloride into potassium sulfate—a significantly less corrosive compound—thereby reducing corrosion rates and deposit growth rates by approximately 50%. This effect may occur over extended periods without associated slagging or fouling. [38]

2.5.3 Non-Technical Barriers to Co-Firing

Several non-technical barriers can hinder the implementation of co-firing biomass with fossil fuels, including: [8, 11. 26]

- **Economic and Political Uncertainty**: There is often uncertainty regarding the level of economic and political support available, such as tax exemptions or fuel subsidies, which can affect the attractiveness of co-firing initiatives.
- **Financial Feasibility**: The economic viability of co-firing is further complicated by unstable biomass prices and an insecure supply chain, making it difficult for power plants to commit to long-term co-firing strategies.
- **Market Liberalization**: The liberalization of the energy market has forced power plants to implement cost-cutting measures to ensure survival. As co-firing often incurs higher costs compared to coal-based energy systems—unless mitigated by subsidies or other forms of support—this can deter investment in co-firing technologies.

2.6 Types of combustion system

Various furnace designs have been developed for the direct combustion of wood, as wood fuels vary significantly in composition, moisture content, size, and combustion technique. The rising costs of fossil fuels and the increasing demand for alternative wood-burning methods have led to a growing selection of furnace designs [38].

When designing a burner, a mathematical analysis is crucial to understand the forces acting on the particles. Numerous researchers have discussed the factors influencing the design of combustion chambers, providing mathematical models that investigate the time required for combustion and the contact duration of solid particles with air. The effectiveness of a combustion chamber for powdered fuel depends on the time needed for complete combustion of each particle, which is influenced by the combustion rate, particle path, and velocity. Furthermore, the combustion rate of any solid fuel is affected by several factors, including:

- The temperature of the combustion chamber.
- The concentration of the air-fuel mixture.
- The turbulence of the fuel particles in relation to oxygen molecules.
- The chemical and physical properties of the fuel itself.

The following combustion systems for wood fuel can be categorized based on the method of wood burning: [24, 35,]

I. Suspension Burner

This type of combustor is designed for smaller, dried fuel particles. In suspension burners, wood particles burn while being propelled in the air.

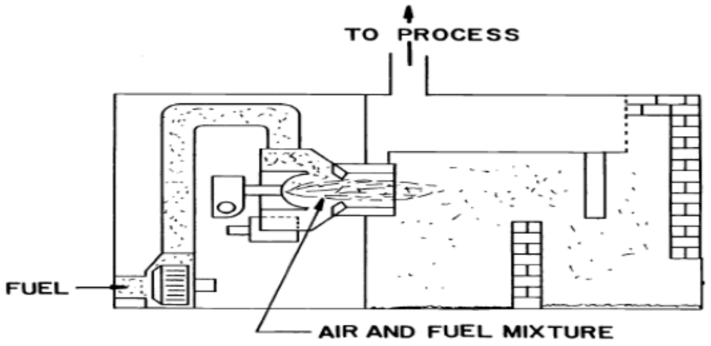


Figure 1. Suspension burner

The ideal fuel particles for this type of burner are less than 0.25 inches in size and typically have a moisture content of less than 15%.

II. Cyclone Firing Systems

Cyclone firing systems are versatile, capable of burning both dry and wet fuels. They can handle wet fuels with moisture content up to 65% and particle sizes up to 4 inches. What sets cyclone firing apart is the tangential delivery of secondary air into the cyclone under high pressure. However, drawbacks include high power consumption, a low turn-down ratio, and limited operational fuel parameters; certain designs can also lead to high NOx emissions due to elevated flame temperatures. [6, 17]

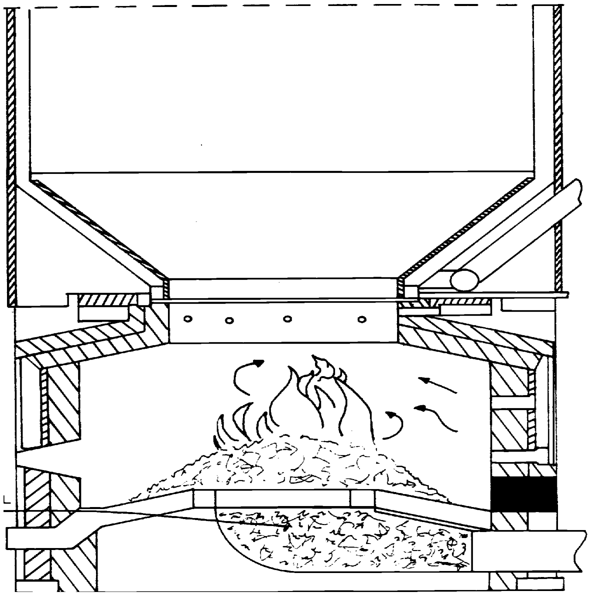


Figure 2. Cyclone burner

III. Fluidized Bed Combustor

The fluidization medium used in this system varies based on the type and properties of the fuel. A fluidized bed combustor consists of a porous floor chamber (distributor plate) filled with a bed of solid inert particles (fluidization medium), such as sand or limestone. Air under pressure (fluidization gas) is passed through the medium at a specific velocity (fluidization velocity) to cause the particles to float and move likes a boiling liquid. This type of combustor can utilize wood fuel particles of any size or shape, with moisture content up to 65%, without prior preparation. In wood combustion, the flame temperature in a fluidized bed is maintained below 2000°F (typically between 1500°F and 1800°F or 815°C to 982°C). This lower temperature extends the life of the materials and prevents ash slagging. However, the two most significant drawbacks of fluidized bed combustors are their high initial costs and substantial power consumption. [18, 21, 39]

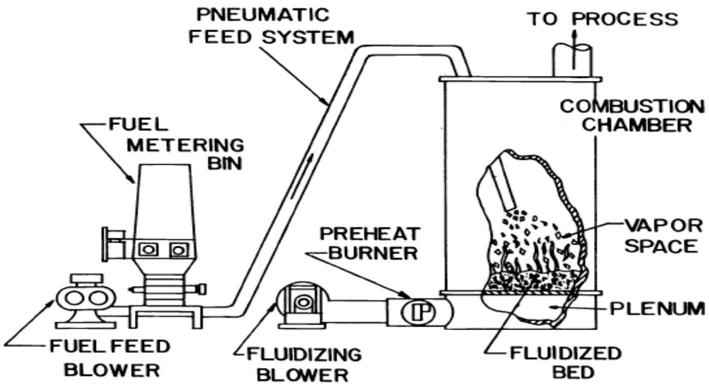


Figure 3. Fluidized bed burner

The burner unit of Maichew board particle looks like this following picture.

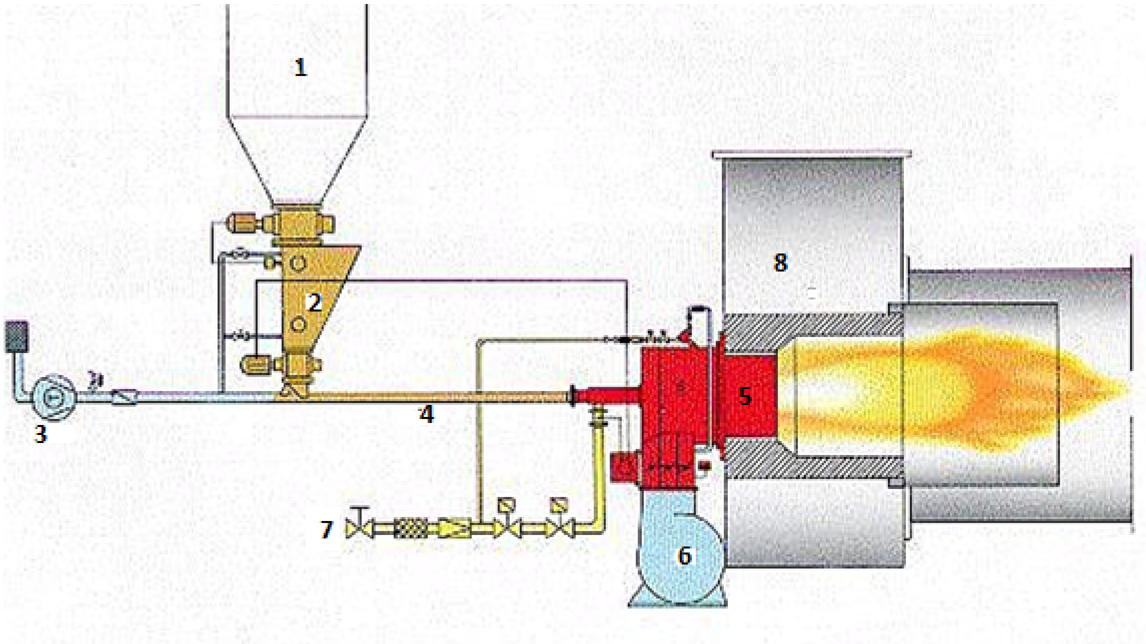


Figure 4. Schematic view of the dust/gas firing system Maichew board particle (*Where 1. Wood dust SILO, 2. Wood dust dosing bin, 3. Delivery air condenser (carrier air blower), 4. Dust conveying pipe, 5. CK - Koerting - dust/natural gas burner, 6. Combustion air fan, 7. Gas fittings group, 8. Hot gas generator)*

2.7 Heat Exchanger

The flue gases from the burner are transferred to the drying system using a heat exchanger, often referred to as a Hot Gas Generator (HGG). Hot air or gases are necessary for drying or other processes, but due to the high level of contamination from combustion, the hot air cannot be in direct contact with the final product, such as wood flakes. The heat exchanger ensures that "clean" hot air enters the flash dryer without coming into direct contact with the diesel or wood combustion byproducts. The design of a hot air generator for a flash dryer must consider these contamination concerns. There are two types of hot gas generators: [9, 41]

I. Direct Type

In the direct type, dilution air or hot recirculating gases are mixed with burner flue gases, and the outlet temperatures can reach as high as 1200°C.

II. Indirect Type Hot Air Generators

Indirect hot air generators consist of a double-shell structure, with the inner shell serving as the combustion chamber and the mixing chamber being refractory lined. The dilution air or mixed gas enters the outer shell tangentially, flowing between the inner and outer shells, and is combined with the hot gases at the end of the combustion chamber. This design helps keep the combustion chamber's steel structure cool. These generators are compatible with oil, gas, and alternative fuel burners. [18]

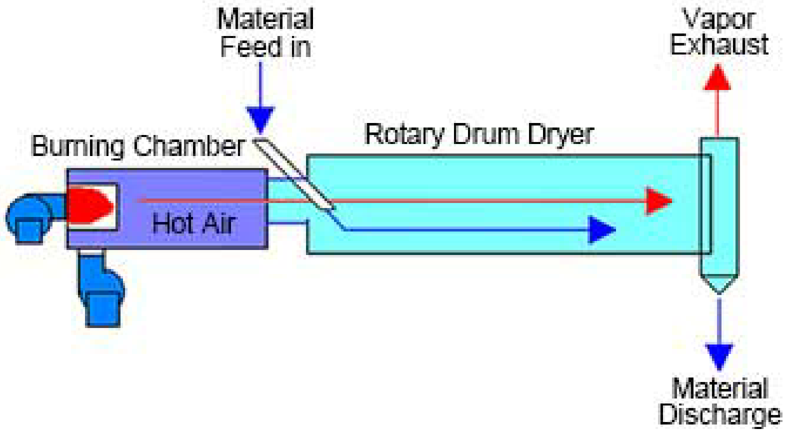


Figure 5. Co-current types of heat exchanger

At Maichew Board Particle, a direct hot air exchanger was used. The flake dryer, connected to a biomass burner, was a continuous flow dryer. The hot gases were drawn before air preheating, and an auxiliary fan forced them through the hot air duct to the front side of the dryer. The hot air duct was connected to the blower inlet of the dryer, allowing control of the hot air temperature and airflow by adjusting the biomass supply rate and the damper opening ratio on the hot air fan.

2.8 Dryer

Drying is the process of supplying heat to wet materials to remove volatiles or moisture through mass transfer. Typically, drying is achieved by thermal techniques, involving heat application through convection from air currents. A material and heat balance is important for assessing dryer performance in terms of evaporation efficiency and thermal energy input.

Types of Dryers

At Mai Chew Board Particle, a rotary drum dryer is used. The drum rotates continuously, with its speed adjustable via a variable-speed drive to adapt to variations in feed quality. The speed of the drum is adjusted depending on the moisture content of the material. If the material is too wet or dry before reaching the knife, the drum speed should be decreased or increased accordingly [3, 9].

Figure 6. Rotary dryer of Maichew bord particle

The inside of the drum is equipped with special tools called flights, which constantly lift the flakes to ensure uniform drying regardless of their size. Larger flakes remain in the drum longer than smaller ones, ensuring proper drying. As the drying process proceeds, the moisture in the flakes evaporates, and when sufficiently dried, the air flow carries the material out of the drum through the outlet.

To guarantee safe dryer operation, the system includes a self-activating substitute load system that injects water into the dryer inlet if the flow of wet material is interrupted. This prevents system overheating. An automatic water injection system is also in place, which activates at various points if an over-temperature situation occurs.

Cyclone Separator

A cyclone separator is used to separate larger and heavier particles from smaller and lighter ones by utilizing a spinning column of gas. The heavier particles are forced to the walls of the cyclone. The Mai Chew Particle Mill (MPM) uses a cyclone separator with a tangential inlet and axial discharge, which is a common type for these systems. [13, 43, 45]

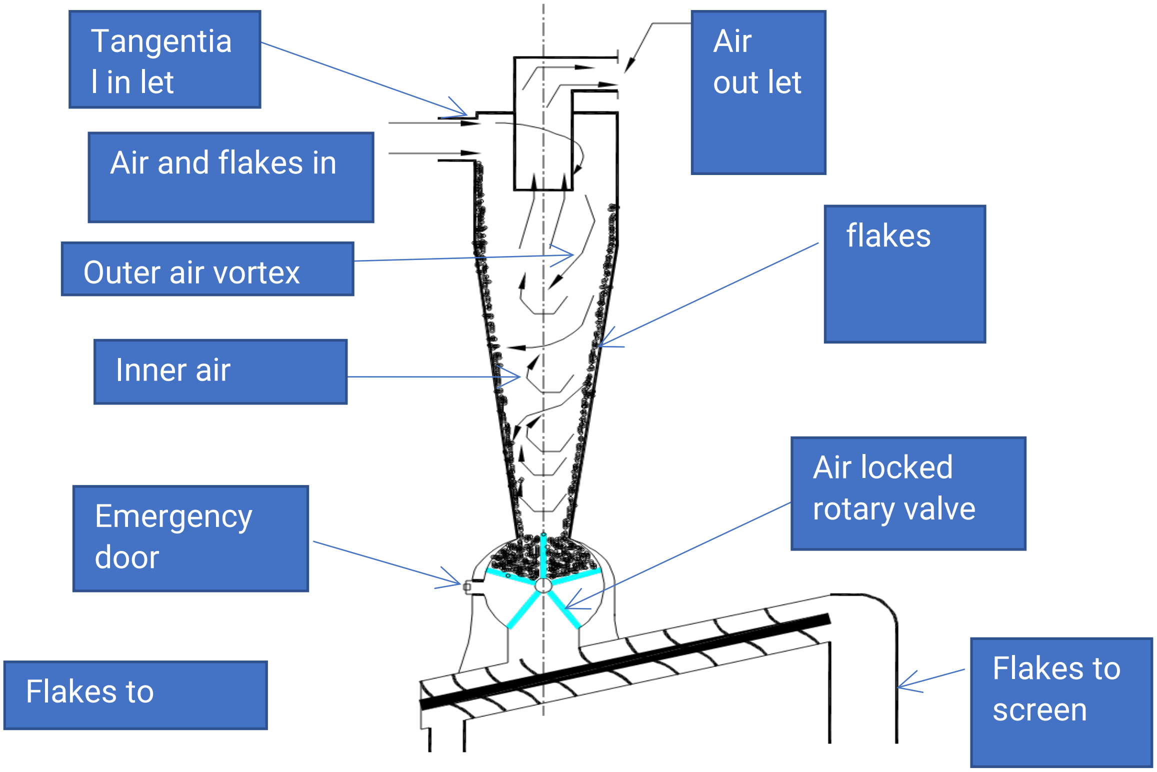


Figure 7. MPM’s cyclone separator

CHAPTER THREE

3. METHODS AND MATERIALS

3. Methodology

The methodology involves a case study of the specific industrial process, utilizing an exploratory and investigative approach to determine the mass and energy balance from the burner to the dryer process. The study was conducted in three main stages:

- The mass and energy balance (MEB) for the burner, chamber, and dryer was analyzed based on the theoretical and analytical methods of thermodynamic laws and fuel combustion equations.
- Air-fuel ratio optimization was performed using Microsoft Excel 16's Solver tool.
- Barriers affecting burner operation with high biomass ratios were identified through literature review, gathering additional data from factories, and personal communication with factory experts.

3.1 Determining the Required Heat

A quantitative analysis of mass and energy balance was carried out to determine the heat supply parameters to the dryer. This analysis involved mathematical calculations of the dryer’s inlet and outlet process requirements, including the conditions of the hot gas (flue gas and air) and the flakes entering and exiting the dryer. The procedure to determine these parameters involved the following steps:

- Identifying the heat required in the dryer per hour.
- Calculating the mass flow rate of the hot gas (a mixture of air and flue gas), and the required amount of air which is added on the chamber.
- Calculating the flue gases exiting the burner based on combustion analysis.
- Performing a balance on the burner inlet and calculating the heat required for the dryer to identify the total fuel mass flow rate.

Flow chart of the burner-dryer process of Maichew factory:

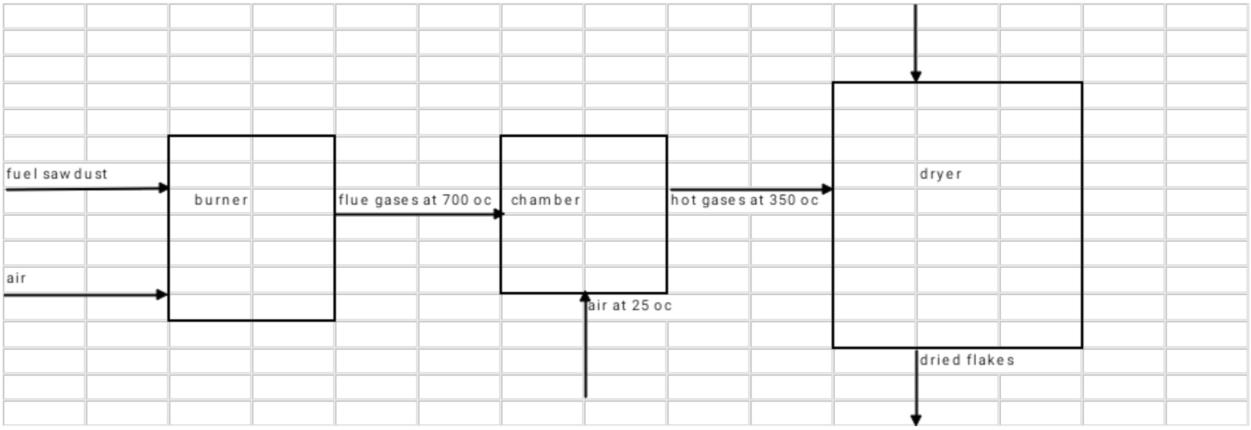


Figure 8. Mass and Energy Balance of the Drier

A. Calculation heat on the dryer:

The flake dryer connected to the sawdust burner was a continuous flow dryer. The flue gases that come from the burner was connected to the blower inlet of the dryer.at the latter ambient air from the environment was mixed with hot gases, which increased the air flow and further decreased the air temperature and air flow to the flake dryer by adjusting the sawdust supply rate and the ratio of dumper opening at the hot air fan.

The following steps were considered when calculating the mass and energy balance for the dryer:

Input mass flow rate and moisture content of the flake: The mass flow rate and moisture content of the wet flakes entering the dryer were determined based on data gathered from the industry survey.

Moisture content (MC) of the flakes is expressed as a percentage per kilogram of the flake.

The mass of water in the wet flakes is calculated using:

$$M_{water} = \%\,MC_{flakes} \times \text{Total wet flakes mass entering drier}$$

MC flakes%, which is moisture content in one kilogram of flake.

Where, M water is mass of total water.

$$\text{Total mass wet flake} - \text{Total mass water} = \text{Mass of dry flakes}$$

Output moisture content of the flake: This refers to the moisture content of the dried flakes, which should meet the factory's recommended moisture level for further processing, typically between 2-3%.

Output moisture= 2–3% of the mass of water

Required output mass flow rate of material: This refers to the mass flow rate of the wet flakes, calculated as:

Mass of dry flakes+2–3% of the mass of water

Water amount in the output material: This indicates the total evaporated water, which is removed from the total entered wet flakes.

Amount of dry matter: This represents the total mass of dry flakes after the water has evaporated.

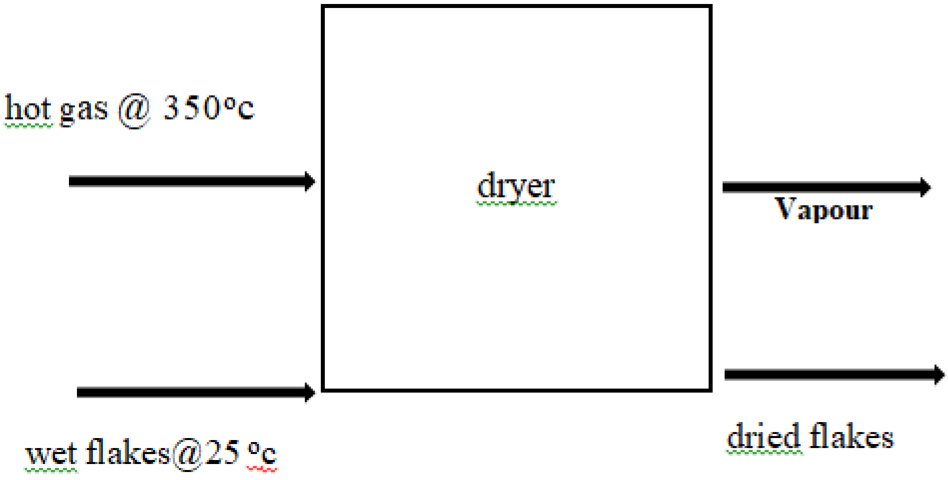


Figure 9. Flow chart of dryer

To calculate the heat necessary to supply to the drier:

Assumption : it is needed the exact measuring of drier efficiency, but here to conduct the study I took there was not any loses on the dryer.

Heat entered to dryer = Heat used to dry wet flakes

we take input to the dryer which is hot air of the flue gases that released from the chamber. The latent heat of vaporazation of water @ 350 °c is known based on engineering tool box. So, to calculate the amount of heat required for the dryer is using by the following formula:

Q(drier)=latent heat evaporation of the water*(moisture of the flake at in let- moisture of Flake out the drier)

B. Mass and energy balance on Chamber

The flue gases come from burner and the air added in chamber together creates hot gas, which is used to dry the flakes when it inters to dryer. The flue gases which come from the burner have a temperature 700 °c. but the dryer needed the hot gas to have 350 °c based on the factory manual so, it needed to add air on the chamber.

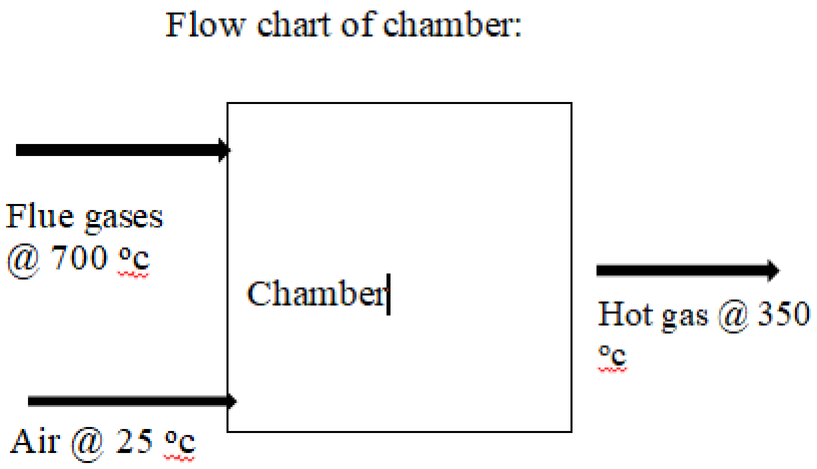


Figure 10. Flow chart of chamber

Energy balance on chamber:

Here is the procedure how to calculate the total flue gases out of the chamber and how much amount of air must add to supply hot gases to dryer.

Assumption: there is no heat loss due to the surroundings of ducts of the chamber.

Q in = Q out

Q in = Qflue gas@700 oc + Q air @25oc

Q out =Qhot gas @ 350 oc

Q hot gas@ 350 oc =Q flue gas@350oc + Q air @350oc

Q in flue gas @700 oc +Q in air @25 oc =Q out flue gas @350 oc +Q out air @350 oc

There is no energy of air at inlet

So, Q flue gas @700 °c= Q flue gas @350 °c+Q air @350 °c

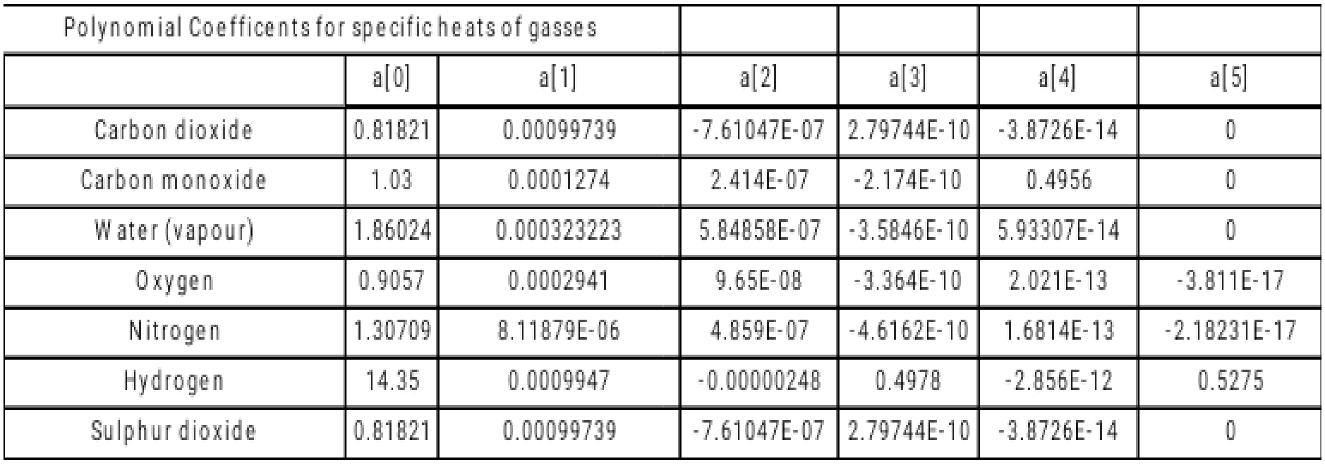
Q flue gases in @700 °c, which comes from burner.

Q flue gas out @350 oc =M flue gas *cp@ T mean *ΔT

=M flue gas * cp@ T mean *(T out -Tin)oc

Cp gasees =f(t) =a[0] +a[1]t +a[2]t2 +a[3]t3 +….., H =mcp@Tmean

Tmean , Is the average temperature of the ambient and the initial temperature of air. Coefficient of the integer's gasses are gained from NASSA.



Polynomial Coefficents for specific heats of gasses						
	a[0]	a[1]	a[2]	a[3]	a[4]	a[5]
Carbon dioxide	0.81821	0.00099739	-7.61047E-07	2.79744E-10	-3.8726E-14	0
Carbon monoxide	1.03	0.0001274	2.414E-07	-2.174E-10	0.4956	0
Water (vapour)	1.86024	0.000323223	5.84858E-07	-3.5846E-10	5.93307E-14	0
Oxygen	0.9057	0.0002941	9.65E-08	-3.364E-10	2.021E-13	-3.811E-17
Nitrogen	1.30709	8.11879E-06	4.859E-07	-4.6162E-10	1.6814E-13	-2.18231E-17
Hydrogen	14.35	0.0009947	-0.00000248	0.4978	-2.856E-12	0.5275
Sulphur dioxide	0.81821	0.00099739	-7.61047E-07	2.79744E-10	-3.8726E-14	0

Where, $T_{\text{out flue gas}}$ =350°c & $T_{\text{flue gas in}}$ =700 °c

Q air $\text{out}_{@\ 350\ ^{o}c}$ =M_{air}*$cp_{@T\ \text{mean}}$*ΔT

=M_{air} *$cp_{\text{air}\ @T\ \text{mean}}$*($T_{\text{out}}$-$T_{\text{in}}$)

Where, $T_{air\ out}=350\ ^{o}c$

$T_{\ air\ in}=25\ ^{o}c$

Q hot gas@$350^{o}c$= Q air out$_{@\ 350\ ^{o}c}$+ Q flue gas out @$350\ ^{o}c$

$$Q \text{ flue gas out@350 oc } = \sum \begin{matrix} hCO2 \\ hH2O \\ hO2 \\ hSO2 \\ hN2 \end{matrix}$$

Where, h is enthalpy of flue gases at a given temperature.

$$hCO2 = m\ CO2 * cp\ CO2@T\ mean *(Tout - Tin)$$

Finally, by using the total summation of flue gases and the hot air which added after the parameters were determined as hot gas that going to dryer.

3.2 Determining the Mass and Energy balance on the burner

I used suspension combustion type of burner, which is separated from the oil burner. The factory of stored sawdust biomass was conveyed to the husk tank by a blower and uniformly supplied to the furnace. Butane used an ignition oil to start burning of the sawdust fuel. The biomass burned around the inner wall of the furnace with a primary air supplied from the environment. The in-furnace temperature was kept below 800 ^{o}c to prevent the corrosion of in furnace material. Because nitrates which are formed if the temperature of burner exceeded more than this temperature.

In the combustion system, the weight of fuel (sawdust) and the weight of air entering the burner should equal the weight of flue gas plus the weight of ash leaving the burner chamber, i.e.,

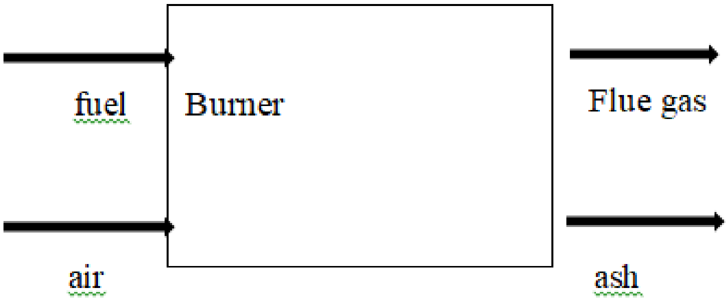


Figure 11. Flow chart of burner

The Mass balance on burner will be: -

Mass fuel + mass air =mass flue gas + mass ash.

3.3 Air Requirement for Combustion

Combustion occurs when fuel reacts with air. To calculate the mass of air required for complete combustion, the following steps are considered:

Determine the Theoretical Mass of air:

The amount of oxygen required to react with a given mass of fuel can be determined by the following stoichiometric reactions:

- $C+O_2 \rightarrow CO_2$
- $4H+O_2 \rightarrow 2H_2O$
- $S+O_2 \rightarrow SO_2$
- $N+O_2 \rightarrow N_2$

The theoretical mass of oxygen required is calculated by subtracting the oxygen content already present in the fuel.

Air composition consists of oxygen and nitrogen:

The air supplied for combustion includes both oxygen and nitrogen. While oxygen participates in the combustion process, nitrogen remains inert and must be considered in the calculations

Air consists of 23% oxygen and 77% nitrogen in mass.

The theoretical mass of oxygen can be expressed as:

0.21×mass of air = theoretical mass of oxygen

Calculate the Mass of Air

The total mass of air required for combustion can be calculated using the formula:

Mass of air=theoretical mass of oxygen/0.23

Calculate the Mass of Nitrogen:

Since nitrogen is an inert gas, its mass is calculated as:

Mass of nitrogen = mass of air×0.77

Stoichiometric and Excess Air Conditions

Stoichiometric combustion refers to an ideal condition where all the fuel is perfectly burned with the exact amount of oxygen. In practice, achieving stoichiometric combustion is challenging because the combustion process involves the mixing of fuel and oxygen in specific ratios. As the reaction progresses, oxygen and fuel are consumed, leaving fewer reactants available in the reaction zone. This leads to the dilution of the remaining reactants by combustion products, such as carbon dioxide, water vapor, and nitrogen, which do not contribute to the reaction. The dilution reduces the probability of remaining oxygen molecules colliding with unreacted fuel particles, making it difficult to ensure complete combustion without introducing excess air. Even with good turbulence, it is unlikely that all the remaining fuel will react with the diluted oxygen. As a result, some unreacted fuel and oxygen may exit the combustion chamber.

To ensure complete combustion, excess air is added, which provides more oxygen than is theoretically required. This excess air increases the likelihood that the remaining fuel will come into contact with oxygen and fully combust.

Excess Air Ratio

The excess air ratio is defined as the additional air supplied to ensure complete combustion. This excess air ensures that the last remaining particles of fuel have sufficient oxygen to combust, although some oxygen may remain unreacted and pass through the system.

The general formula for excess air ratio is:

$$\% \text{ EA} = \frac{\text{MRA}}{\text{MRath}} * 100$$

Where, MRA is actual mass flow rate air to the given mass of fuel

MR_{ath} is mass rate air gained theoretically.

% EA is percentage of excess air to fuel

The excess air ratio added to combustor also contains oxygen and nitrogen.

$$\text{MRA} = \text{EA} * \text{MRath}$$

Actual Mass rate of oxygen needed to burn the fuel completely=actual mass rate of air *n0.21

Actual mass rate of air=actual mass rate of oxygen/0.21b

Actual mass of nitrogen entered to combustor =0.79*actual mass rate of air

The unreacted oxygen = Actual Mass rate of oxygen needed to burn the fuel completely-theoretical mass of oxygen

Mass Balance of Air

Air is composed of both oxygen and nitrogen, but in the combustion process, only oxygen participates as a reactant. The mass balance of air can be described as follows:

- Mass of air in the combustion burner = mass of oxygen used in combustion.
- Mass of air exiting the combustion burner = mass of nitrogen in the flue gas + mass of unreacted oxygen in the flue gas.

Air-Fuel Ratio Optimization Method

To ensure optimal combustion at a given burner temperature, the air-fuel ratio was optimized using Microsoft Excel 2016 Solver. This tool allows for the adjustment of air and fuel inputs to achieve the best possible combustion efficiency and performance.

3.4 Energy Balance of Burner Combustion

Heat, which is a form of energy, is released during combustion. The energy involved in the combustion process can be described in terms of enthalpy. The energy balance in the burner's combustion process accounts for the heat generated, the energy input from the fuel, and the heat transferred to the air or flue gas.

I. Energy Input of the Fuel:

Energy input of each mass of dry fuel is equal to its lower heating value which is the net calorific value of the fuel. which excludes the latent heat actually available from the combustion process in practice for capture and use.

The gross calorific value (GCV), or high heat value, measures the total (maximum) amount of heat that is produced by combustion. However, part of this heat will be locked up in the latent heat of evaporation of any water present in the fuel before combustion (moisture) or generated in the combustion process.

It should be pointed out that this is based on the assumption of complete combustion (all the carbon in the fuel forms carbon dioxide and all the hydrogen in the fuel forms vapor).

The total energy input of the dry wood dust fuel is then equal to:

$$Qwd = MR\,wd * LHV \ldots\ldots 4$$

- Qwd = Energy of wood dust
- MRwd = Mass flow rate of wood dust
- LHV=lower heating value

II. Energy output:

Which are the released flue gases from a given mass of the fuel and air after complete combustion takes placed on the burner.

$Q_{\text{flue gas}}=\sum \text{Enthalpy flue gases}^{*\Delta T}$

$H=mcp@T_{mean}$

$=M_{flue\ gas}*Cp_{flue\ gas}\ @Tmean*\Delta T$

Where, $Q_{flue\ gas}$ =heat of flue gases

$Cp_{flue\ gas}$ @Tmean=specific temperature of flue gases at mean temperature.

ΔT=delta of temperature in and out of the burner.

We consider some assumptions to perform the energy balance. These are:

- Both the air and the fuel take as dry base
- Lower heating value of the fuel has been considered
- Flue gases of enthalpy must be constant with time variation
- There is no kinetic energy, potential energy and work done

Enthalpy of reactant and product are considered with reference to standard pressure and temperature (1ATP, and 25 ^{0}C)

III. Energy Input with Air

The energy input with combustion air refers to the energy contained in the air entering the combustor, which contributes to the overall combustion process. If the air is pre-heated, a significant amount of energy can be added to the system. In this study, the burner operates with air at atmospheric temperature (25°C).

However, if the factory operators to use pre-heated air, the following steps can be used to calculate the energy contribution from the air entering the combustor:

- **Determine the specific heat capacity of air**:
- **Calculate the temperature rise**: Subtract the initial atmospheric temperature (25°C) from the pre-heated air temperature.
- **Energy calculation**: Multiply the mass flow rate of the air by the specific heat capacity and the temperature rise to obtain the total energy input from the air.

This amount (heat) energy of air is calculated as follows:

Ea = MRa*Ha …………. equation (5)

where, Ea is the amount of heat(energy) in combustion air

Ha is the enthalpy of combustion air

MRa is the mass flow rate combustion air

Ha $=\int_{'amb}^{'out} cpdt$ ……………..equation (6)

Cp gasees =f(t) =a[0] +a[1]t +a[2]t2 +a[3]t3 +….., H =mcp@Tmean

Where, cp is the specific heat capacity of gases, Δt is temperature difference of air and Tmean the average temperature of in and after heated the air.

3.5 Estimating Heat Losses

Heat losses occur when energy is either released to the environment or through the unburned fuels due to ashes These losses can be categorized as follows: radiation loss, energy loss due to incomplete combustion

For burning sawdust particles, a suspension type burner is more suitable than other types. The heat losses described below are based on the assumptions related to this type of reactor.

I. Heat Loss Due to Unburned Carbon in the Ash (ELash)

In bagasse furnaces, heat loss due to unburned carbon in the ash is typically around 2% of the total heat generated. If the carbon content of the ash is known, this heat loss can be calculated as:

- Elash = Mass of carbon in the ash per kg of fuel× Carbon heating value

However, it is usually estimated as 2% of the total fuel heating value.

II. Heat Loss Due to Radiation and Other Indeterminable Losses (ELR)

Radiation losses and other undeterminable heat losses, such as those due to inefficiencies in the system, are typically estimated to account for about 6% of the total heat generated.

III. Data and Information Collected for the Burner's Mass and Energy Balance

For this research at Maichew Particle Board Factory, data was collected from various sources, including archival records, documentation, interviews, direct observations, and measurement readings. Generally, two types of data were gathered: primary data and secondary data.

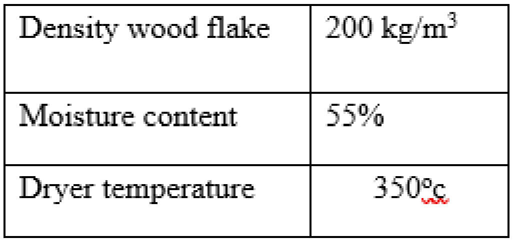
Primary data was obtained directly by the researcher through studies of the specific problem, including direct observation, personal interviews, and conversations with experts.

Secondary data was sourced from existing research in the same or related problem areas. This data included the review of documents, websites, and historical records relevant to the research.

3.6 Raw Data Maichew Particle Board Industry

According to the factory's manual, the dryer is capable of drying up to 80 m³ ton of wood chips per hour. However, due to various limiting factors, the actual drying capacity is currently around 60 m³ ton of chips per hour.

Table 2. Data of flakes

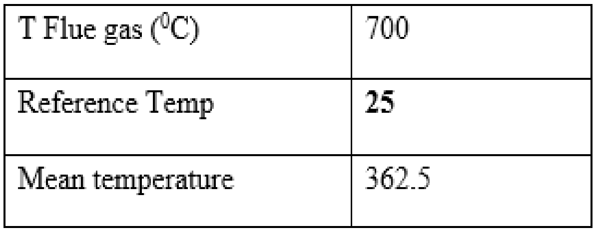


Density wood flake	200 kg/m^3
Moisture content	55%
Dryer temperature	350ºc

Burner

Maichew board particle factory has furnace combustor used to generate hot gases. Its name is called Körting combustion chamber. The combustion chamber set up to 700 °C due to hot gas generation for flakes drying processes.

Table 3. Data of burner temperature



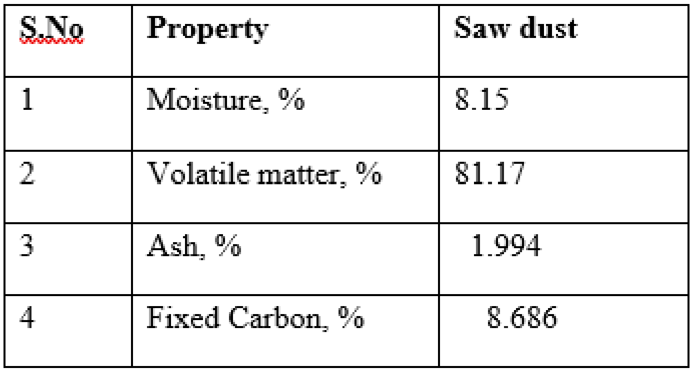
T Flue gas (^{0}C)	700
Reference Temp	**25**
Mean temperature	362.5

IV. Sawdust Properties Data

Physical and chemical property

Proximate analysis of eucalyptus dust. This data was taken from the Netherlands data Philly.

Table 4. Result of proximate analysis of sawdust



S.No	**Property**	**Saw dust**
1	Moisture, %	8.15
2	Volatile matter, %	81.17
3	Ash, %	1.994
4	Fixed Carbon, %	8.686

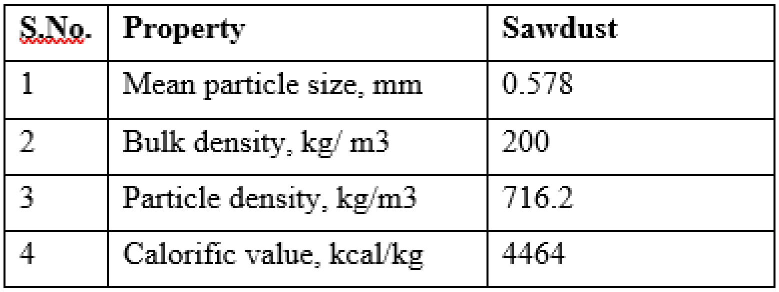
Ultimate analysis of eucalyptus of saw dust,1 kg basis with lower heating value of 16.7 MJ/kg. This indicates an elemental composition that evaluated from an experimental determination of data.

Table 5. Experimental result for the ultimate analysis of sawdust

Ultimate Analysis	wt%
Hydrogen	6.16
Carbon	50
Nitrogen	0.2
Sulphur	0.069

Oxygen	43.5
Ash	0.071
Total	100

Table 6. Physical Properties of sawdust



S.No.	Property	Sawdust
1	Mean particle size, mm	0.578
2	Bulk density, kg/ m3	200
3	Particle density, kg/m3	716.2
4	Calorific value, kcal/kg	4464

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Operational balance of drying

As explained in chapter three in the methodology part analysis of the demand of hot air to dryer comes on the first. The dryer of the factory has a capacity to dry 60 m^3 flakes.

- Density of wood flakes 200 kg per m^3.
- Mass flow rate of flakes (wet wood chips) Maichew particle bord dryer =12,000kg/hr.
- And its moisture content of flakes is exceeded up to 55%.

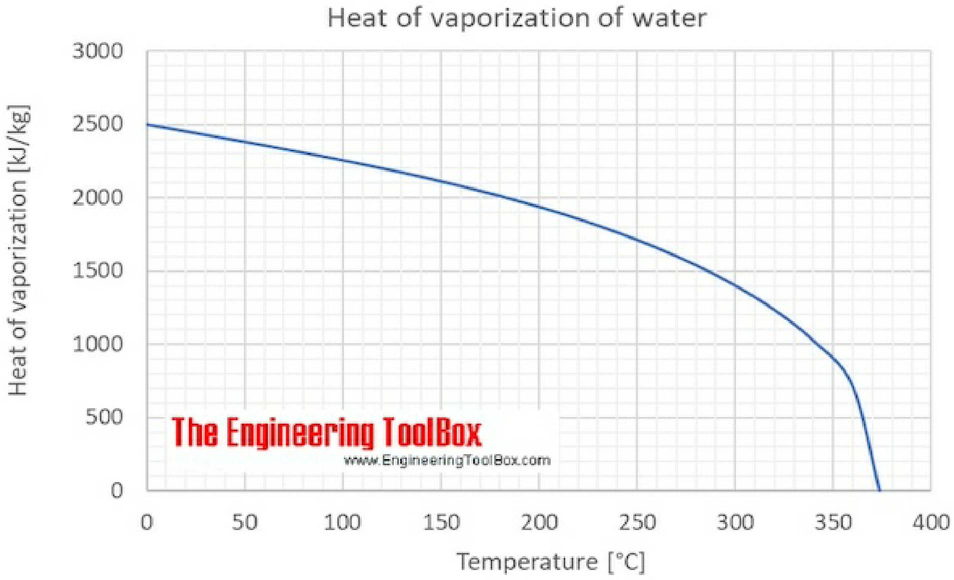
By applying heat from the chamber burner, the chips can be dried to achieve a moisture content of 2-3%.12,000*55%=12,000kg/hr.*0.55=6600 kg is the mass of moisture. [5, 18]

- The mass of the dry product is also 5400 kg.

= 0.025*6600 = 165 kg of total moisture of the product (the out let of the chips).

To calculate the heat necessary to supply of the drier: -

$Q(_{drier})$ =latent heat evaporation of the chips*(moisture of the chips at in let- moisture of out the drier) Latent heat of evaporation of chips for one kilogram water at 350 ^{o}C is 900



kj/kg

Figure 12. Heat evaporation versus temperature

(6600kg-165kg) = 6,435 kg moisture.

900 kJ/kg*6435kg= 5,791.5MJ/hr.

4.2 Analysis of burner input and output parameters

A. Mass Balance of Burner Combustion

The mass flow rates of carbon, hydrogen, oxygen, nitrogen, ash, and water in the fuel are determined based on the fuel's composition. The following assumptions are made:

- All nitrogen remains unchanged and acts as an inert component.
- All hydrogen reacts completely to form water (H_2O).
- Carbon reacts to form either carbon monoxide (CO) or carbon dioxide (CO_2), or remains unburned, depending on the combustion conditions.

By applying a mass balance approach, the final composition and mass flow rate of the flue gas are calculated based on these reaction products. To achieve optimal combustion efficiency, an energy balance is also conducted, comparing the energy input, energy output, and heat losses in the system.

B. Mass Balance of Combustion Process

- **Carbon (C)** reacts with oxygen (O_2) to form carbon monoxide (CO) or carbon dioxide (CO_2), depending on combustion conditions.
- **Hydrogen (H)** reacts with oxygen to form water vapor (H_2O).
- **Sulfur (S)** reacts with oxygen to form sulfur dioxide (SO_2).

The mass balance of the combustion products, including the unreacted nitrogen and ash, is then calculated to determine the final composition of the flue gas.

Table 7. Molecular weight of elements of sawdust

Fuel composition	Mass (ultimate analysis) eucalypts	Molecular weight
Hydrogen	0.061	1
Carbon	0.5	12
Nitrogen	0.002	16
Sulphur	0.00001	14
Oxygen	0.435	32

Mass in = Mass out

Mass fuel + mass air = Mass of flue gases

0.5 X

a. $C + O_2 \longrightarrow CO_2$

12 32

X O_2=mass of oxygen which is used to form CO_2

Mass of CO_2 is equal to the sum of the two mass fractions (C & O_2).

0.06 X

b. $4H + O_2 \longrightarrow 2H_2O$

32

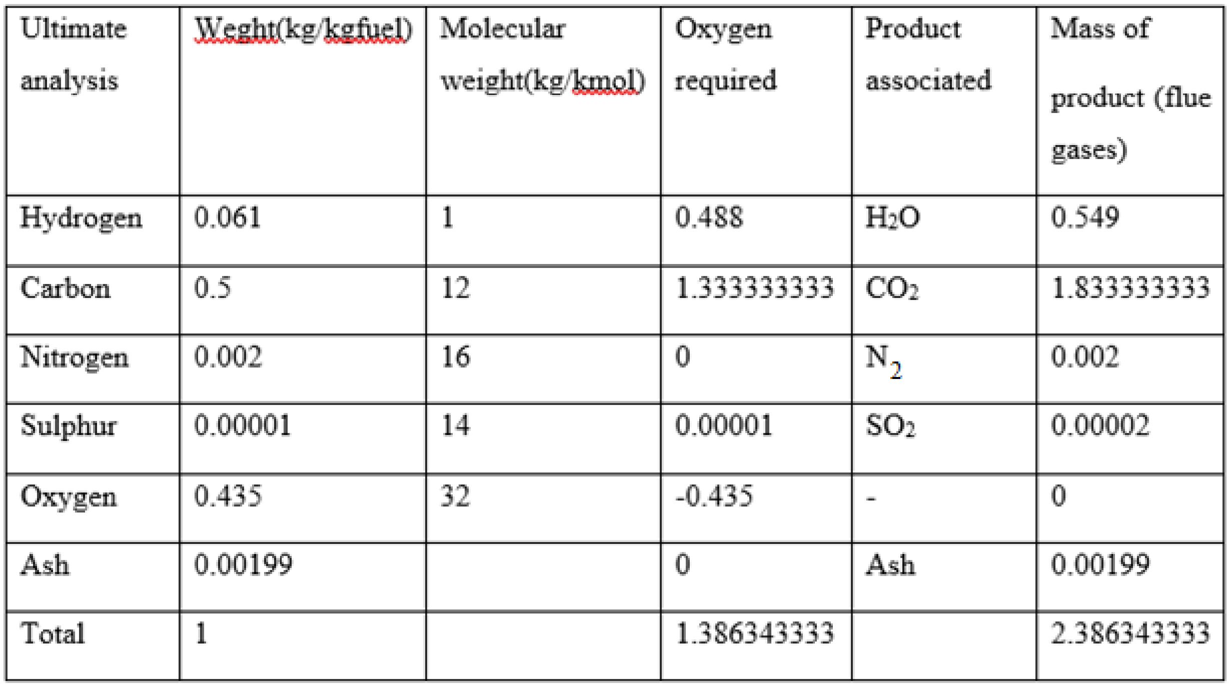
X O_2 = Mass of water(vapor)= 0.0002 X

C. $S + O_2 \longrightarrow SO_2$

32 32

XO_2 = Mass of SO_2=

Table 8. Composition of dry Eucalyptus sawdust wood and oxygen required



Ultimate analysis	Weght(kg/kgfuel)	Molecular weight(kg/kmol)	Oxygen required	Product associated	Mass of product (flue gases)
Hydrogen	0.061	1	0.488	H_2O	0.549
Carbon	0.5	12	1.333333333	CO_2	1.833333333
Nitrogen	0.002	16	0	N_2	0.002
Sulphur	0.00001	14	0.00001	SO_2	0.00002
Oxygen	0.435	32	-0.435	-	0
Ash	0.00199		0	Ash	0.00199
Total	1		1.386343333		2.386343333

4.3 Mass Balance of Air Flow Rate

To calculate the amount of oxygen required for combustion, the oxygen already present in the wood is subtracted from the total oxygen required for combustion. This gives the oxygen that must be supplied by the air:

Oxygen required – Oxygen present in fuel = Oxygen needed from air

In this case, it is determined that 1.386 kg of oxygen is required from ambient air to combust the fuel ideally. Since ambient air contains only 23% oxygen and 77% nitrogen by volume, the amount of air needed for combustion is calculated by dividing the required oxygen by the mass percentage of oxygen in the air.

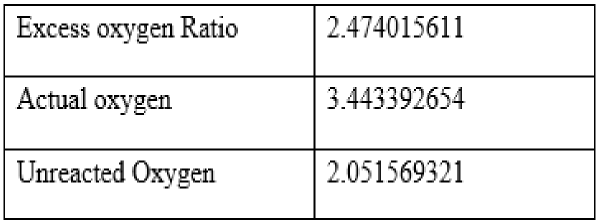
Air required= Oxygen needed from air /0.23

,. This value represents the theoretical air-to-fuel ratio, but in practice, complete combustion requires additional air beyond this theoretical value.

The air supplied beyond the stoichiometric requirement is known as **excess air** and is expressed as a percentage of the stoichiometric air quantity. Excess air ensures that there is enough oxygen to achieve complete combustion, reducing the amount of unburned fuel and improving efficiency.

Table 9. Result of total air fuel ratio for optimum combustion of sawdust fuel

Air requirement Kg/kg fuel	14.97127241
Nitrogen in air (kg/kgfuel)	11.52787976
Nitrogen in FG (kg/kgfuel)	11.52987976



Excess oxygen Ratio	2.474015611
Actual oxygen	3.443392654
Unreacted Oxygen	2.051569321

The results indicate that for the combustion of 1 kilogram of sawdust fuel, an additional 2.47 kg of excess air is required. This excess air calculation considers only the mass of oxygen needed for combustion.

Actual oxygen refers to the exact amount of oxygen required to completely burn each particle of fuel. However, after combustion occurs, some oxygen remains unreacted. In this case, the analysis shows that 2.05 kg of unreacted oxygen is released with the flue gases for every 1 kilogram of sawdust fuel burned.

The total mass of air supplied from the environment to burn the fuel, including the excess air, is calculated to be 14.97kg for one kilo gram of fuel.

Since nitrogen is inert at 700°C, it does not react with any of the fuel's components. Therefore, the mass of nitrogen in the air and the nitrogen content in the fuel both exit the combustion process together with the flue gases.

4.4 Estimation of Heat Losses

Heat losses in the combustion process reduce the overall efficiency and must be accounted for. The major sources of heat loss include unburned carbon in the ash and losses due to radiation and other undeterminable factors.

A. Heat Loss Due to Unburned fuel in the Ash (Lash)

For bagasse and similar furnaces, heat loss due to unburned carbon in the ash is typically estimated to be around 2% of the total fuel heating value. If the carbon content in the ash is known, the loss due to this unburned carbon can be calculated using the formula:

$$\text{Lash} = \text{total calorific value of fuel}*2\%$$

$$\text{Lash} \approx 334 \text{ kJ/kg}$$

B. Heat Loss Due to Radiation and Other Undeterminable Losses (LR)

Heat loss due to radiation and other unmeasurable factors is generally estimated at about 6% of the total heat generated in the system. This accounts for approximately:

$$\text{LR} = 1002 \text{ kJ/kg}$$

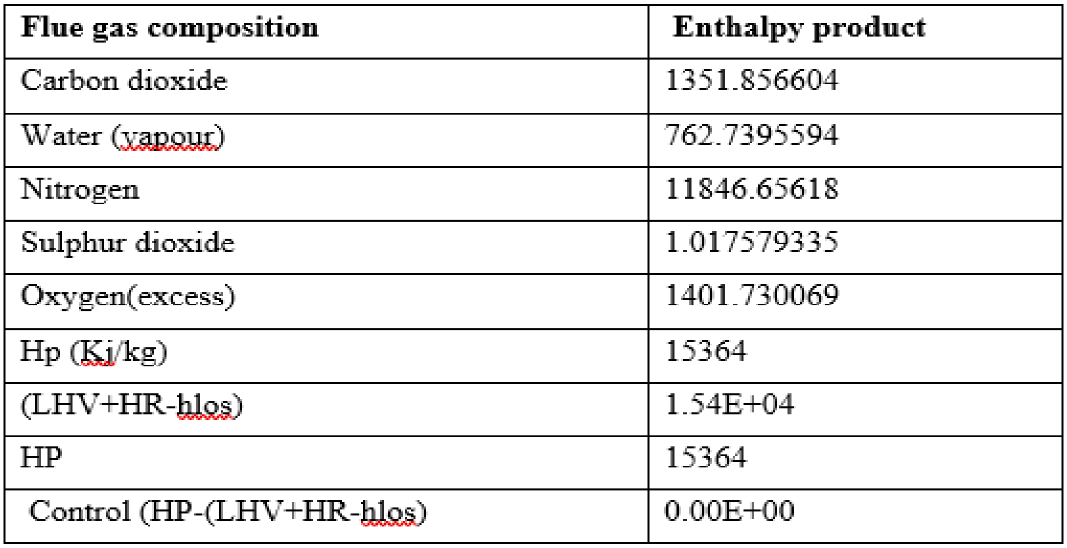
The combined heat losses from radiation are calculated as:
Total energy losses=1336 kJ/kg

4.5 Energy Output

Energy output is the total summation of all enthalpy of flue gases for one kilogram of fuel sawdust. The primary source of energy output is the heat carried by the flue gas leaving the combustor at a high temperature. To achieve optimal combustion efficiency, maintaining the proper excess air-to-fuel ratio is essential. The minimum burner temperature for optimal combustion is set at 700°C, ensuring that excess air facilitates complete combustion while minimizing energy losses. Because nitrates can form if the temperature of burner exceeded more than this which are called the toxic gasses.

The toxic pollutants gases from burners are Nox and their composition is influenced by combustion conditions. Nitrogen monoxide formation is generated in burner in which the temperature is in the range of 1200 ◦ C-1450 ◦ C [32]. The designers of the burner must know the amount of air needed for complete combustion, anticipated flue gas composition, at a given temperature in order to control the emissions and toxic gases formed. Conditions such as oxygen concentration, residence time, temperature and mixing turbulence have big influence in the formation of these pollutants. High combustion temperature combined with high oxygen concentration, residence time, and mixing turbulence reduces the quantity of CO produced but increase the possibility of the formation of NOx. The oxygen and carbon dioxide concentration in the effluent gas are a useful indicator of the combustion performance.

Table 10. Enthalpy result of from one kilogram of sawdust



Flue gas composition	Enthalpy product
Carbon dioxide	1351.856604
Water (vapour)	762.7395594
Nitrogen	11846.65618
Sulphur dioxide	1.017579335
Oxygen(excess)	1401.730069
Hp (Kj/kg)	15364
(LHV+HR-hlos)	1.54E+04
HP	15364
Control (HP-(LHV+HR-hlos)	0.00E+00

All those results were calculated with excel Microsoft based on the empirical calculations. The 0.00E+00 control part shows that the combustor is runs at optimum combustion rate with its given mass of air.

4.6 Air-Fuel Ratio Optimization

The air-fuel ratio was optimized using the Microsoft Excel Solver program to determine the optimal thermal energy output. This method calculates the exact amount of excess air needed at a given temperature to maximize the heat released by the combustor.here the objectives and constraints are caloric value of the sawdust fule and the excess air ratio respectively.

Solver Optimization Report (Microsoft Excel 16.0)

Result: Solver found a solution. All constraints and optimality conditions are satisfied.

Solver Engine:

Engine: GRG Nonlinear; Solution Time: 0.016 Seconds; Iterations: 0 Subproblems: 0

This optimized air-fuel ratio ensures efficient combustion and maximizes energy output from the fuel, considering the operational conditions of the burner.

4.7 Analysis on the chamber

The total hot gas that passed through the chamber was used to remove moisture from the flakes in the dryer. To eliminate 6,435 kg of moisture from the entering flakes, the dryer required 5,791.5 MJ/hr of energy. Given that one kilogram of sawdust fuel generates 15.36 MJ/kg of hot gas, the burner must combust approximately 376.95 kg/hr of sawdust fuel to provide the required 5,791.5 MJ/hr.

To completely combust 376.95 kg/hr of sawdust fuel, approximately 6,180.93 kg/hr of air from the environment is needed. The excess air ratio used is 2.47.

Table 11. Result for the input and output value of chamber

Input chamber	**Product**
Q flugas@700 oc	15364
temp air@25	25^{o}c
Q air @ 25 Oc	0
temp flue gas in	700 ^{o}c
Chamber output	
Temperature of the flue gas & air mixture (hot gas) at ___out put	350^{o}c
Q flugas @350	product enthalpy
Water (vapour)	-7.30567E+12
Nitrogen	-6308.642386
Sulphur dioxide	-0.564921157
Oxygen for excess	-756.3755327
Q flue gas out chamber	-7.30567E+12
Q air out chamber (KJ)	7.30567E+12
mass of air (Kg)	29193468203
Q air out chamber (KJ/Kg)	7.30567E+12
Q hot gas (KJ/Kg)	15364
Q of hot gas (MJ/Kg)	15.364

4.8 discussion of the Mass and Energy Balance

The mass and energy balance fuel combustion is a crucial method for accounting for both useful energy outputs and losses within the furnace. As discussed in previous chapters, the energy balance of the Maichew particle board furnace can be simplified to state that the total energy input into the furnace equals the sum of the useful energy outputs and the energy losses. The primary sources of heat entering the furnace are sawdust, heavy oil, and combustion air. This thesis has primarily focused on quantifying the amount of heat generated for the drying system based on the utilization of a high biomass ratio.

To determine the energy input from sawdust, the components of the wood must be considered. These components can vary significantly depending on the wood species used. The most commonly utilized species at Maichew is eucalyptus sawdust, which has an energy content of approximately 16.7 MJ/kg on a dry basis. This calorific value is essential for calculating the overall energy contributions of sawdust to the combustion process, ultimately impacting the efficiency of the dryer and the overall production process.

4.9 Air fuel ratio

Another critical input into the boiler is the combustion air, which is sourced from within the burner plant. The energy input derived from wood chips diminishes if the temperature of the combustion air is low. Given that the heat generated from the burner is primarily directed towards the drying system, it is essential that combustion occurs at an optimal temperature of around 700°C.

To optimize combustion efficiency, the combustor must operate with a maximum level of excess air while maintaining the lowest effective combustion temperature. This study emphasizes the importance of adjusting the air-fuel ratio to prevent incomplete combustion of the wood chips. For a combustor operating at a temperature of 700°C, it has been determined that 16.39 kg of air is required for the complete combustion of 1 kg of sawdust fuel.

4.10 Mai chew Particle board fuel use and burner situation

The Mai chew factory currently relies heavily on sawdust as its primary biomass input, but it does not utilize other biomass sources, such as leaves and branches from eucalyptus trees. To maximize the use of available biomass resources, it is recommended that a burner be designed specifically for biomass fuel utilization.

Transitioning to biomass as an alternative fuel not only enhances the economic viability of the plant by reducing reliance on expensive fossil fuel purchases, but it also contributes to lowering environmental emissions. Currently, the burner consumes up to 90 liters of heavy oil per hour to dry approximately 60 m^3 ton of flakes. By shifting entirely to biomass, the factory can mitigate the impact of rising fossil oil prices and reduce operational costs. But there are many obstacles when the factory depended only on biomass fuels.

4.11 Barriers to Biomass Maximization at Maichew Particle Board Factory

The barriers to maximizing biomass utilization at the Maichew particle board factory can be classified into technical and non-technical challenges. One of the key technical barriers is the lower calorific value of biomass compared to other fuels, as it contains around 70% volatile matter. This requires larger burners to generate sufficient flue gas for energy production.

Biomass particle size at the factory ranges from fine sawdust (1/100 inch) to larger particles like bark. The particle size and shape significantly affect the combustion process and the burner feed system. Larger particles require bigger feed valves and take longer to burn, potentially leading to unburned fuel in the ash pit. On the other hand, fine particles like sawdust have a higher chance of causing bridging in the feed system, especially when the material has a high aspect ratio, such as mulch.

At the Maichew factory, the burner was designed for heavy oil, with sawdust used as a supplementary fuel. Sawdust has a higher heat release rate, but larger biomass particles can exceed the system's designed capacity, impacting both the combustion efficiency and the fuel handling system. This mismatch between particle size and burner capacity can lead to operational challenges, including inefficiencies in the combustion process and strain on the fuel handling equipment. Therefore, careful consideration of particle size and burner design is critical to optimizing biomass co-firing at the factory. this thesis work is only considered sawdust type of biomass. We can also classify the combustion reactors belong with the option to work in separated with current burner to enhanced biomass cofiring,

Most of the time suspension type of burner was very appropriate to burn sawdust biomass.

Suspension firing is designed and used for properly sized and pre-dried wood fuel which, used wood particle particles to mixed with air and are to burned in suspension. However, larger or high moisture content particles tend to fall and are not burned in suspension. This type of firing requires the most restricted fuel particles both in size (less than 0.25 inch) and moisture content (usually less than 15%). Pre-drying and size reduction of the fuel is necessary since most wood fuels do not meet required conditions when they are received in a power plant. The most important design parameter in a suspension burner is heat release per furnace volume. Typical values are about 14000 Btu/hr per cubic foot of furnace volume.

Suspension burners are manufactured with capacities up to 80x106 Btu/hr fuel input.

The reactor consists feeder, fan which used to sucks the fuel from nozzle part of the feeder and it can blow tangentially to the furnace.

after burned the fuels the flue gas exits the furnace and goes to dryer to supply heat for drying. A cyclone part used to separate ash particles from the flue gases to exhausting to atmosphere.

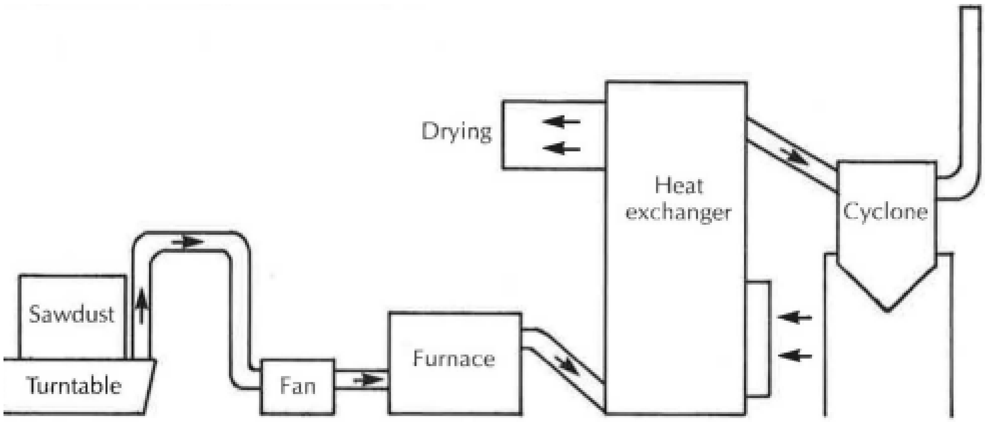


Figure 13. Diagram of suspension reactor

The second one is fluidized bed combustion reactor. This type of reactor has its own combustion control system, such as air fuel ratio, and can ability to burn wide range of biomass fuel type.

We have also several modification ways to improve the existing burner to increased biomass cofiring. here are the followings:

- Dual-fuel injection system: this modification way is used to improve the mixing of air and fuel which worked by adding a separate injection.
- Burner nozzle modification: to burn large particles of biomass it needed to maximized the nozzle part of the burner.
- Use insulation for the combustor: to minimized the heat which is penetrated from the combustor.

The recommended reactor can be integrated with system as a secondary burner which are separated with oil burner reactor that feed in to the same flue gas line existing burner.

Here in the below outline shows how the integration of the new reactor with oil burner seems like;

1, install the separated reactors

2, common flue gas line,

3, control air fuel ratio system to balance the heat that come from the biomass and oil burners.

4, the mixed flue gases will be goes in to the dryer system to evaporated the moisture content of the flakes. Here the following diagram of integrated cofiring reactor

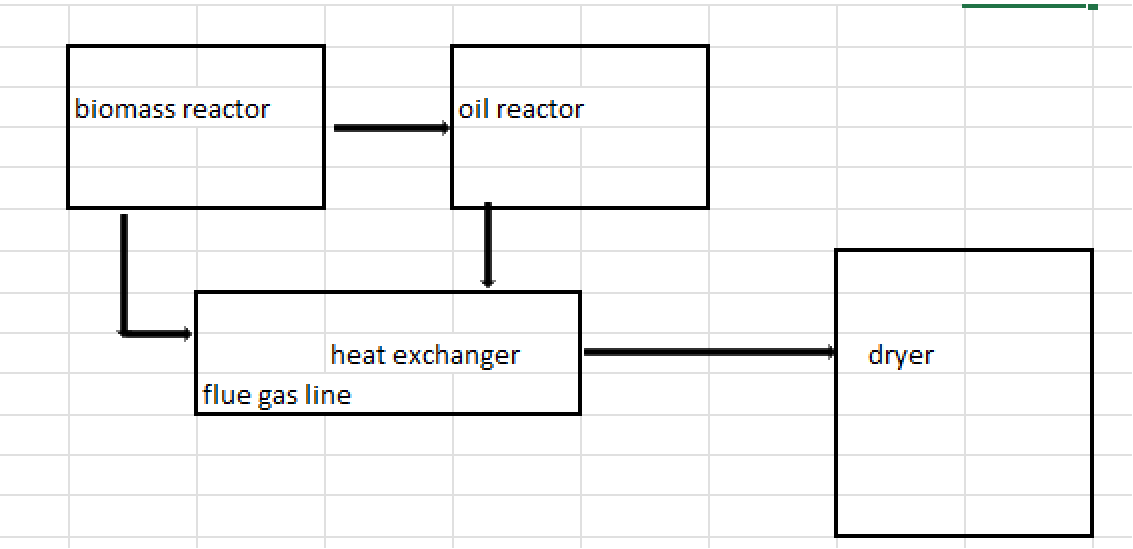


Figure 14. Integrated cofiring reactor

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Data collected from the Maichew factory reveal that the average cost of delivered oil is 60 birr per liter. Given the current operational limits of 8 hours per day, the factory consumes approximately 720 liters of oil daily, leading to an annual oil expenditure of around 1,768,000 birrs. This high operational cost underscores the need for more sustainable and cost-effective fuel alternatives.

This study has provided a comprehensive analysis of the heat released from a high ratio of sawdust biomass and its implications for the operational efficiency of the Maichew factory's combustion system. The findings reveal that combusting 376.95 kg/hr of sawdust generates approximately 5791.5MJ/hr of heat energy, a significant contribution to the factory's overall energy needs.

To ensure optimal combustion, the analysis shows that the existing air supply must be adjusted to meet the theoretical requirements. Specifically, the actual air needed for combustion, taking into account the excess air ratio of 2.47, amounts to about 16.31 kg of oxygen for every kilogram of sawdust which is the air comes from the environment. The actual oxygen needed to burn completely the fuel exceeded 3.44 kg of oxygen. The excess air is crucial for ensuring complete combustion, reducing the potential for unburned fuel, and optimizing energy release.

Furthermore, it was calculated that the dryer, which is essential for removing moisture from wood flakes, requires approximately 5791.5MJ of heat energy to evaporate 6,435 kg of moisture per hour. This heat demand underscores the necessity for a reliable and efficient combustion process, as the heat generated from the sawdust combustion must sufficiently meet the dryer’s energy requirements. To maximize thermodynamic efficiencies, it is concluded that the combustor should operate at an adjusted level of excess air of 16.3 kg per hour for one kilo gram of fuel with maintaining a combustion temperature of 700°C. Operating under these conditions not only enhances combustion efficiency but also improves energy utilization within the system.

Furthermore, independent studies indicate that the factory has access to substantial quantities of unused and discarded wood residues, which are often available at little to no cost. This availability presents an excellent opportunity for the factory to enhance its sustainability efforts while significantly reducing fuel costs. However, for successful co-firing projects to be implemented, it is crucial that operators can access this biomass without incurring additional transportation costs, ensuring that the economic benefits of using biomass are fully realized.

By integrating biomass into its energy mix, the Maichew factory can improve its 80% of the overall economic performance while contributing to environmental sustainability.

This approach not only mitigates the dependence on expensive fossil fuels but also capitalizes on readily available biomass resources. Ultimately, transitioning to co-firing with biomass positions the factory as a more environmentally responsible and economically viable operation, enabling it to navigate the rising costs of fossil fuels while enhancing its contribution to renewable energy initiatives.

In conclusion, achieving an optimal air-fuel ratio operating at a lower combustion temperature is critical for enhancing the combustion process's efficiency. By focusing on these parameters and selecting the appropriate combustion unit, the Maichew factory can effectively utilize biomass, reduce operational costs, and minimize environmental impacts, thereby positioning itself for improved sustainability and performance in its biomass energy production efforts.

5.2 Recommendation

Based on the findings of the current study, several key recommendations are put forth to further enhance the efficiency and sustainability of the Maichew factory's combustion processes. These recommendations aim to address the gaps identified during the research and to pave the way for future investigations.

I. Furnace and Burner Design Optimization:

The study also highlighted the types of combustion units suitable for this application. Based on literature and manufacturer recommendations, a suspension-type combustor was identified as the most appropriate choice.

This type of combustor which is found on figure 13 can ability of handling high biomass ratios and effectively mixing fuel and air, ensuring efficient combustion and thermal output.

Further investigations should be conducted to explore the shape and dimensions of the furnace, as well as the form and size of the burner. In particular, research should focus on identifying the most suitable burner types for alternative fuels beyond sawdust, such as leaves and branches. This includes evaluating different combustion unit designs to optimize performance and efficiency when utilizing diverse biomass feedstocks.

II. Exploration of Alternative Biomass Fuels:

A significant amount of experimentation is needed to evaluate the potential of alternative fuel sources, such as leaves and branches. This research should focus on assessing the combustion characteristics, energy content, and emissions profiles of these biomass materials. By doing so, the factory can determine the feasibility and advantages of integrating these fuels into its existing systems. Understanding the combustion behavior of these materials will provide a more reliable, applicable, and comprehensible framework for biomass utilization.

III. Pilot Testing and Demonstration Projects:

Conducting pilot tests and demonstration projects with various biomass types can provide valuable insights into their performance within the existing infrastructure. These projects should include detailed monitoring of emissions, efficiency, and overall operational costs. The data gathered can help refine operational practices and contribute to best practices for co-firing strategies.

IV. Economic Analysis of Biomass Utilization:

An in-depth economic analysis should be conducted to assess the long-term financial benefits of using biomass as a fuel source compared to fossil fuels. This analysis should consider not only direct cost savings from fuel substitution but also potential savings from reduced environmental compliance costs and waste disposal fees.

V. Stakeholder Engagement and Training:

Engaging stakeholders, including factory employees, local biomass suppliers, and environmental agencies, is crucial for the successful implementation of biomass co-firing initiatives. Providing training and resources to staff about the operation and maintenance of new combustion technologies can ensure smoother transitions and enhance overall operational efficiency.

VI. Environmental Impact Assessment:

Future studies should include comprehensive environmental impact assessments to evaluate the potential reductions in greenhouse gas emissions and other pollutants resulting from the switch to biomass fuels. These assessments will not only support compliance with environmental regulations but also bolster the factory's sustainability credentials.

By addressing these recommendations, the Maichew factory can enhance its biomass utilization strategies, improve operational efficiency, and contribute to a more sustainable energy future. These initiatives will not only support the factory's economic viability but also align with broader environmental goals in the region.

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