

**ENERGY MANAGEMENT PLAN OF AN OPTIMIZED WOOD-FIRED
BOILER IN A TEA PROCESSING FACTORY IN KERICHO,
KENYA**

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**A THESIS SUBMITTED TO THE SCHOOL OF EDUCATION IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE
OF DOCTOR OF PHILOSOPHY IN TECHNOLOGY EDUCATION
(MECHANICAL TECHNOLOGY OPTION) IN TECHNOLOGY
EDUCATION, SCHOOL OF EDUCATION, UNIVERSITY OF ELDORET,
KENYA**

2025

DECLARATION

Declaration by the Candidate

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DEDICATION

This thesis is dedicated to my beloved wife, Mary Wangari, and my wonderful children, Derrick and Lewis. Their unwavering love, steadfast support, and infinite patience have been a constant source of strength for me throughout my journey as a PhD student. To Mary, thank you for being my rock and for your encouragement, which inspired me to push through the challenges I faced along the way. Your understanding and sacrifices have made it possible for me to pursue my academic goals.

To Derrick and Lewis, you have been my motivation and joy. Your laughter and love have brightened my long days of study, reminding me of the importance of family above all else. This dedication also extends to all the families who support their loved ones in their educational pursuits, for their faith and encouragement lay the groundwork for success. May this work inspire not only my family but also others who strive to pursue their dreams against all odds of life.

ACKNOWLEDGEMENTS

I wish to express my profound gratitude to the Almighty for the divine guidance and resilience that have facilitated my attainment of this significant milestone in my academic journey. I am particularly thankful to the University of Eldoret, and especially the School of Education Technology, for providing the robust framework that enabled me to pursue my academic aspirations. I extend my heartfelt appreciation to my supervisors, Prof. Peter Okemwa and Dr. Isaac Nangendo, for their expert mentorship, invaluable insights, and steadfast support throughout the course of my PhD program. I am also grateful to the academic community at the University of Eldoret, including Dr. Hosea, Dr. Dimo, Prof. Kitainge, Prof. Ferej, Prof. Simiyu, Prof. Kerre, and Prof. Kafu, for their constructive feedback, encouragement, and contributions that have significantly enriched the quality of my research.

I am eternally indebted to my beloved wife, Mary Wangari, for her unwavering love, patience, and moral support throughout my academic endeavors. I also wish to acknowledge the unconditional encouragement and love from my children, Derrick Kamunge and Lewis Thini. Additionally, I am sincerely appreciative of the support from my extended family and friends, whose emotional and financial assistance proved invaluable in sustaining me throughout this scholarly pursuit. May the blessings of the Lord continue to shine upon each and every one of you.

ABSTRACT

Energy resources are generally constrained and costly, resulting in a gap between the rising demand for energy and the available supply. Tea factories are no exception, as many rely on boiler as a source of energy for their operations. The high cost of fuel has led these factories to adopt challenging solutions, such as using wood as a combustion source for boilers. Given that wood is an expensive source of fuel, implementing effective energy management strategies is crucial to ensuring sustainable productivity. This research aimed to optimize boiler energy usage and develop an energy management plan (EMP) to enhance boiler efficiency and minimize gas emissions. The study was grounded in three theories: the Theory of Moisture Sorption, the Phlogiston Theory, and the Lavoisier Theory. The researcher applied the research onion framework, focusing on factors such as air-fuel ratio, the boiler's surface heat loss, the fuel's moisture content, and boiler flue gas losses. A fuzzy logic controller was designed to optimize the combustion process of the boiler. Simulations revealed that the fuzzy logic controller significantly improved the AF ratio, boosting efficiency from 78% to 81% during combustion. The optimized parameters enabled the creation of an energy management plan (EMP), which was validated using a continuous-time dynamic model. Validation results indicated an initial linear temperature increase, suggesting enhanced heat transfer and accelerated heat absorption by water. Near the boiling point of water (373.15 K or 100°C under standard atmospheric pressure), the graph plateaued, as additional heat contributed primarily to the phase change from water to steam. Applying the developed EMP in industrial settings would improve boiler combustion efficiency, enhance productivity, and reduce emissions, thereby mitigating environmental pollution.

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LIST OF ABBREVIATIONS AND SYMBOLS

°F	Degree Fahrenheit
Btu	British thermal unit
Btu/ft³	British thermal unit per cubic foot
m³	Cubic Meter
CH₄	Methane
C₂H₆	Ethane
Cl	Chlorine
CO	Carbon Monoxide
CO₂	Carbon dioxide
HCl	Hydrochloride
H₂SO₃	Sulphurous Acid
H₂SO₄	Sulphuric Acid
Ph	potential of hydrogen
N₂	Nitrogen
NO	Nitrogen oxide
NO₂	Nitrogen dioxide
NO_x	Nitrogen oxides
O₂	Oxygen
S	Sulphur
SCO₂	Supercritical carbon dioxide
SO₂	Sulphur Dioxide
APH	Air Preheater
ASME	American society of mechanical engineers
ASTM	American Society for Testing and Materials
CTC	Cutting Tearing and Curling
DOE	Design of experiments
DMAIC	Define, Measure, Analyze, Improve, and Control
DOSH	Directorate of occupational safety and health
EMP	Energy management plan
EFB	External Fired Boilers
EMAS	Eco-Management and Audit Schemes
EPA	Environmental Protection Agency

ESP	Electrostatic precipitators
FBC	Fluidized Bed Combustion
FGR	Flue gas recirculation
FDF	Forced Draft Fan
GCV	Gross calorific value
GDP	Gross Domestic Product
HAPs	Hazardous Air Pollutants
HCN	Hydrogen cyanide
HDO	Heavy Diesel Oil
ICI	Industrial, Commercial, and Institutional
ID	Induced Draft
IS	Indian standards
KNBS	Kenya National Bureau of Statistics
LDO	Light Diesel Oil
LP	Liquefied Petroleum
LPG	Liquid Petroleum Gas
NAAQS	National Ambient Air Quality Standards
NCV	Net calorific value
NRV	Non-Return Valve
PAHs	polycyclic aromatic hydrocarbons
PM	Particulate Matter
Ppm	Parts-per-million
RCA	Root cause analysis
RDF	Refuse-derived fuel
SI	International System of Units
SOP	Standard operational procedures
SPC	Statistical process control
TDS	Total dissolved substance
TOE	Tonne of oil equivalent
UNEP	United Nations Environmental Programme
VOC	Volatile organic compounds
VSD	Variable speed drive
WHRB	Waste Heat Recovery Boiler

CHAPTER ONE

INTRODUCTION

1.1 Overview

This chapter presents a comprehensive introduction to the research, detailing the contextual background, problem statement, study objectives, formulated hypotheses, research scope, and significance of the study, underlying assumptions, theoretical framework, and conceptual framework. It delineates the expected outcomes of the research and establishes the overall direction for the study.

1.1.1 Background of the study

Optimizing boiler combustion processes in industrial settings has gained significance due to limitations in fuel availability and the rising energy demands. In academia ongoing research in wood fired boilers has consistently explored alternative energy sources. Thermal combustion of solid fuels in wood fired boilers has remained a critical component of energy provision for many industrial applications. In Kenya's tea processing factories and kericho in particular, a large part of boiler energy is derived from firewood. In this study optimization of air/fuel ratio and effectively controlling fuel characteristics can improve boiler system efficiency (Kamil.K, 2021).By controlling surface heat losses, fuel uptake in the boiler can be reduced significantly, which by extension leads to lower operational costs of the system and a significant decrease in environmental pollution emanating from gas emission (zhao et al, 2015).

Additionally, wood fired boilers are supplied with equipment that controls air-fuel mixture and water, with the primary output being superheated steam depending on the process requirements. The integration of data monitoring equipment in wood fired boilers it's possible to effectively enhance control strategies, such as fuzzy logic, which

analyzes and regulates combustion processes (Boqun et al., 2015). Given the popularity of such monitoring systems of boilers in tea processing industries, fuzzy logic-based control methods are increasingly adopted for boiler management.

Tea processing is an energy-intensive process, in stages such as drying, grading, and packaging. A study by the United Nations Environment Programme (UNEP), approximately 85% of the sector's total energy consumption is linked to thermal energy, with the remaining 15% related to electrical energy (Akenji & UNEP, 2015). Consequently, energy-related expenses constitute about 30% of total tea production costs (AHK, 2014). Drying is the most energy-intensive stage in tea processing, primarily relying on steam to prevent enzyme denaturation. According to Veronica K et al, (2024), optimizing the drying process can lead to some deductions in costs, but sustainability remain a great challenge. Figure 1.1 presents the typical stages of tea processing, illustrating the necessity for a boiler, which provides the most economical form of energy for these activities. Additionally, Mwangi (2017) emphasizes the need for effective energy management practices within the Kenyan tea sector.

Current energy conservation efforts are focused on processes that consume the bulk of steam energy, such as withering and the CTC (Cutting, Tearing, and Curling) process, as indicated in Figure 1.1.

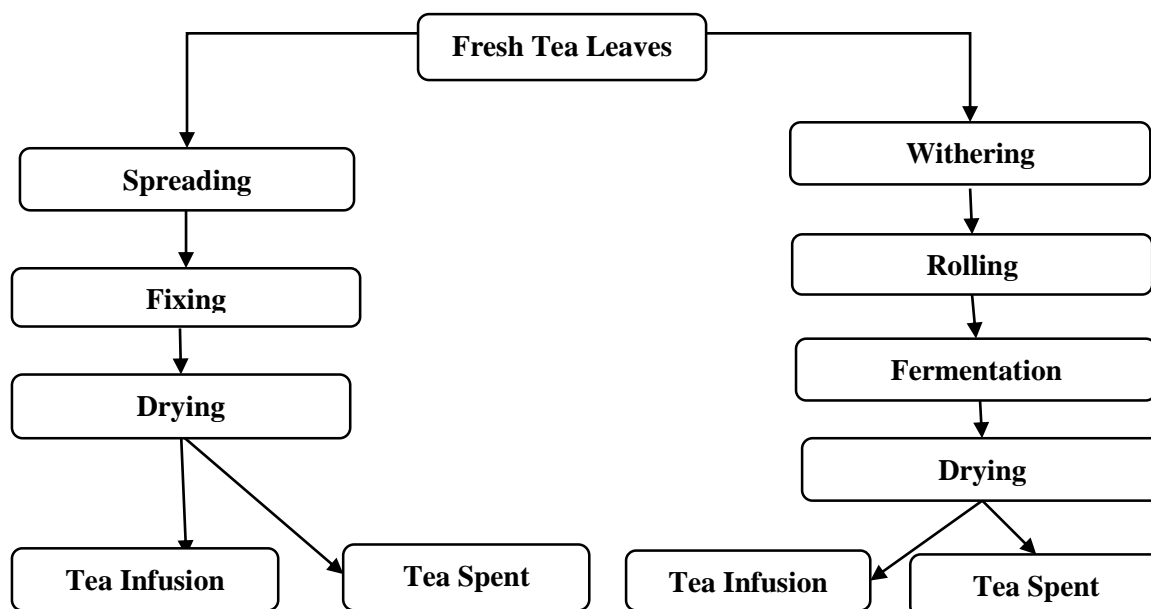


Figure 1.1 Steps in tea processing

(Source: Tea factory under study)

1.1.2 Energy in tea processing

Industrial productivity serves as a key factor of development, which significantly affects a country's Gross Domestic Product (GDP). According to (Sifuna, 2019) energy demand in Kenya currently constitutes about one-third of industrial energy requirements, a trend that has either remained stable or increased gradually over the past 15 years, reflecting a shift away from energy-intensive industries and a growing emphasis on energy conservation. In the tea processing industry, steam energy is widely utilized. Data from Kenya bureau of statistics indicates that steam energy consumption could represent as much as 35-40% of overall energy usage in the industry (KNBS, 2018). The type of steam produced by a boiler typically varies according to pressure and temperature. Figure 1.2 depicts the temperature enthalpy diagram used in thermodynamics to visualize the behavior of water as it undergoes phase changes, particularly relevant to steam production. In tea processing factories, superheated at a

temperature above 100 degrees is the common steam used for drying tea as illustrated in the figure 1.2 shown below.

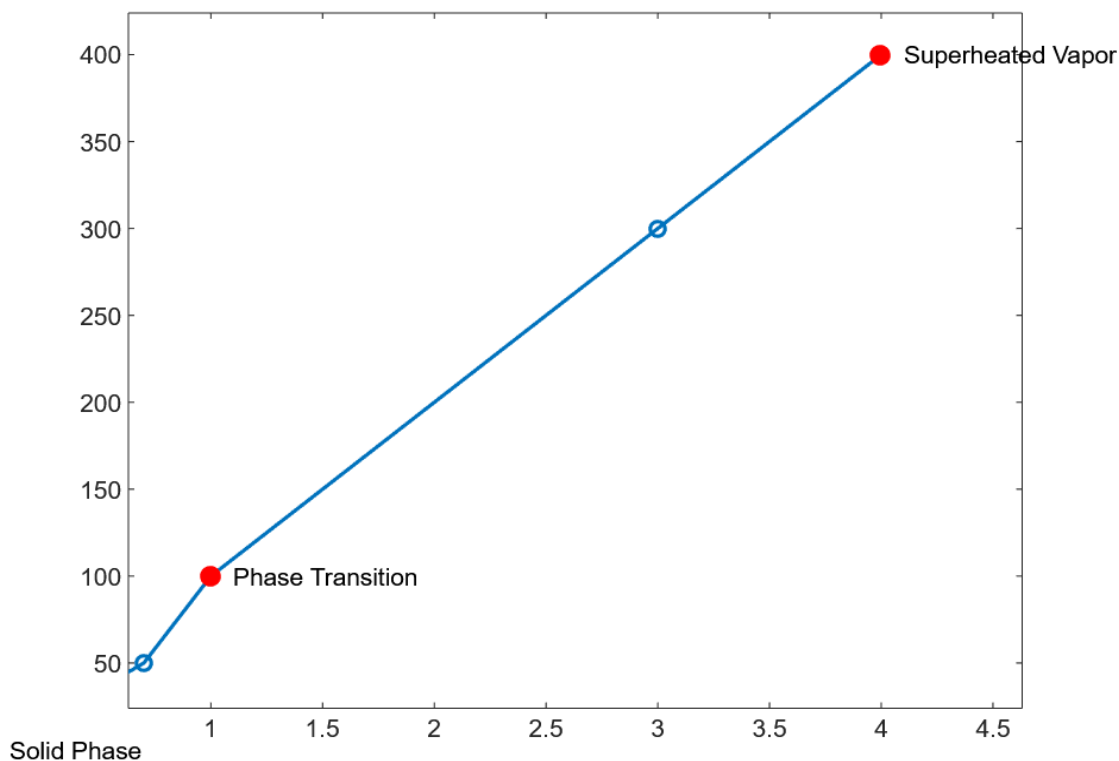
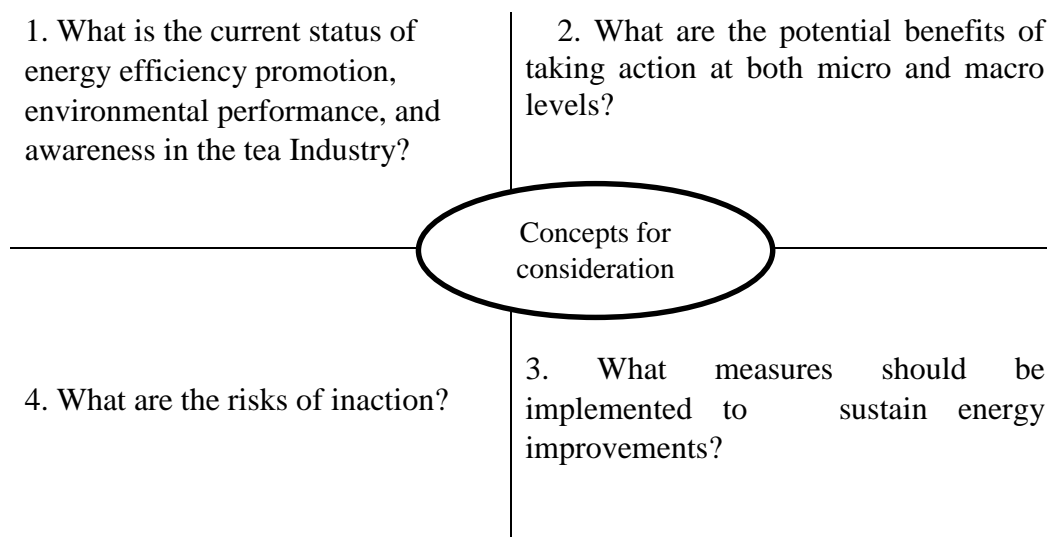


Figure 1.2: Phase change during steam production

1.1.3 Energy saving opportunities in tea factories

Sustainable development strategies in the tea industry prioritize significant long-term threats to reductions in greenhouse gas emissions, securing diverse and competitive energy supplies through environmentally responsible methods. These efforts aim to decrease the impact of persistent pollutants, enhance waste management, and address climate challenges, including climate change and biodiversity, oceans, and forests. This focus raises several pertinent questions:

Table 1.1 Energy sustainability concepts

Kenya has initiated several measures to boost energy and environmental performance. In its development plan, the country has identified the sector's central role, aiming to enhance its contribution from 8.4% to 15% under (Kenya, 2020). While these initiatives encourage adherence to action plans, it is ultimately up to companies to adopt measures that recognize their potential benefits while improving profitability. The field of energy conservation, commonly referred to as Energy Management, is not a novel concept (Mwangi, 2017). With the current ease of access to information, resources that can aid in enhancing energy and environmental performance are readily available. Additionally, environmental performance can be recognized within environmental management frameworks, including International Standard ISO 14001 and Eco-Management and Audit Schemes (EMAS), which generally contribute to improved business practices by highlighting environmental responsibility. Although there have been efforts to enhance energy efficiency in tea industrial processes, significant potential for improvement remains. Traditionally, the potential for energy savings in these processes has been assessed using energy efficiency indicators. This perspective

allows for the development of methodologies to quantify exergy losses and exergy efficiency in boilers (Behbahaninia, Ramezani, & Hejrandoos, 2017). If best practices are implemented today, it is anticipated that overall steam energy use efficiency could improve by 10-25%. Should an organization commit to enhancing its energy and environmental performance, subsequent matters include management commitment, awareness, accountability, and the influence of corporate culture. The integration of software tools into nearly all business operations has also benefited energy and environmental systems through ongoing research and development. Utilizing these tools can transform energy projects from uncertain risks into reliable investments. Energy systems performance modeling, investment appraisal tools, and active systems control and optimization are now available in large organizations and could be standardized across business processes once energy and environmental considerations become integral to corporate values.

To optimize a system, two critical considerations are a definitive characterization of the system, particularly the delineation between the system and its environment, and a judicious selection of performance criteria to be met. Various energy, environmental, and economic objectives necessitate specific criteria for minimizing energy consumption, managing non-recoverable heat losses, and maximizing the beneficial output related to energy efficiency. This study adopts a generalized criterion that encompasses four objectives within a steam energy system, with distinct weighting factors assigned to each objective. The focus of the research is a solid-fuel firewood boiler, wherein thermal losses are evaluated across multiple scales. Fuzzy logic optimization techniques are employed, utilizing diverse distributions of weighting factors, and fuzzy rules are established that align with optimization results from the existing literature.

Three primary stages of steam production are scope for optimization: input, process, and output of the system. The successful implementation of energy management plan described in this study for some tea processing factories in Kenya has demonstrated that various operational strategies can lead to meaningful energy savings (Karambu G et al, 2020). Some of the key factors in systems optimization include enhancing the energy production, minimizing heat losses during distribution of steam, and reducing the environmental contamination through combustion byproducts. Steam energy has become largely applicable globally in the tea factories, largely contributed by the growing complexity of steam generation equipment. These steam systems require skilled operators to prevent wastage during generation storage and transfer of heat in the processes lines.

In a convectional wood fired boiler setup, water serves as the raw material and has to be treated to ensure efficient steam production. Wood fuel is burned in the presence of oxygen to generate the heat necessary to convert water into steam. The combustion process produces flue gases, which pose health hazards, emphasizing the importance of strict safety protocols in boiler houses.

Besides this, one of the major challenges for modern wood fired boilers is optimizing operational performance to maximize steam energy production. This research uses a novel methods which strategizes at improving boiler system efficiency by maintaining environmental protocol established by existing regulations. The study strived to identify critical areas in a boiler vessel where heat losses are high (Hashim et al., 2020). By enhancing boiler efficiency it's very crucial to address environmental concerns, such as greenhouse gases emissions reduction which are associated with industrial boiler operations. This study focuses on improving boiler steam energy efficiency, reducing

losses that are associated with the distribution leading to mitigation of the environmental impact of combustion byproducts in the system.

1.1.4. Purpose of the Study

The main goal of this study is to improve the efficiency of the boiler system, which leads to significant cost savings in Kenya's tea processing operations over time. This provides a key area for potential savings by enhancing combustion performance and reduction of fuel and air consumption, thereby optimizing the boiler's operation. The study explored the application of fuzzy logic as an advanced novel control method. In recent years, fuzzy logic has gained popularity for its ability to effectively manage complex, nonlinear processes like boiler operation. The researcher developed fuzzy sets, fuzzy rules, and fuzzy logic to design an Energy Management Plan (EMP) aimed at tackling real-time challenges associated with boilers under study. The EMP sought to mitigate the environmental impact of greenhouse gas emissions, reduction of energy losses, and improvement of overall boiler performance. By implementing these strategies, the study demonstrated how effective energy management plan can lead to substantial long-term cost reductions in steam generation, promoting more sustainable and efficient boiler operations in tea factories in Kenya.

1.2. Statement of the Problem

The performance of wood-fired boilers under study falls short of optimal operational efficiency and environmental standards due to a combination of operational challenges. High and ever fluctuations in the moisture content of the wood fuel used in the boiler lead to inconsistent combustion, resulting in unstable steam production that can negatively impact the quality of tea processing. Additionally, inadequate surface insulation causes significant heat losses, reducing the boiler's thermal efficiency,

increasing fuel consumption, and contributing to higher emissions of greenhouse gases. Furthermore, improper or inconsistent air-fuel ratios impair combustion efficiency, leading to incomplete burning, increased pollutant emissions, and further energy wastage. These combined issues contribute to poor steam generation, high operational costs, and environmental concerns, underscoring the need to investigate and improve the operational practices of wood-fired boilers to enhance their energy efficiency and environmental compliance while ensuring consistent steam quality for optimal process in tea processing.

Development of practical industrial strategies in addressing these challenges involves an energy management plan tailored to the specific conditions of wood-fired boilers in tea factories in Kericho Kenya. The energy management plan incorporates an advanced fuel quality monitoring the air fuel ratio, strategies for upgrading insulation and flue gas control. In Implementing this EMP the aim is to reduce energy wastage, lower emissions, and improvement of the overall boiler performance which ultimately results in cost savings and environmental control benefits.

This strategic approach in this research directly provides solutions to boiler operational issues such as inconsistent fuel supply and incomplete combustion. By monitoring and controlling fuel quality, operators can optimize combustion parameters to reduce waste. Real-time feedback mechanisms for adjusting air and fuel would further control efficiency and reduce gas emissions. Improved insulation would significantly lower surface heat loss which in long run reduces operational costs and environmental impact. Overly, this research sought to equip operators of the boiler system with practical competencies and skill to achieve optimal performance, reduce costs, and lessens environmental footprints. The implementation of this comprehensive energy

management plan offers a straightforward, technology based on solutions that requires minimal or no additional training, promising to improve the sustainability and profitability of wood fired boilers within the tea processing industries in Kenya.

1.3 Objectives and Scope

1.3.1 Main objective

The main objective of this research is to develop an energy management plan of an optimized wood fired boiler in a tea processing factory in Kericho, Kenya. This was achieved by controlling air/fuel ratio and fuel consumption during the combustion process, which helped in optimizing boiler performance. Improved combustion led to higher combustion efficiency within the boiler system.

1.3.2 Specific Objectives

The main objective was broken down into four specific, achievable goals namely:-

- i. Investigate the effect of moisture content of wood fuel on the efficiency and operational performance of wood fired boiler system in the tea factory.
- ii. Evaluate the relationship between air fuel ratio and overall efficiency in the wood-fired boiler system.
- iii. Assess the environmental implications of flue gas emissions produced by the boiler and identify potential mitigation strategies.
- iv. Analyze surface heat losses within the boiler system and determine their effect on overall energy efficiency.

1.4 Research hypothesis

A research hypothesis is the statement the research study sets out to prove or disprove. The research study was guided by the following hypotheses:

H0₁: Moisture content in wood fuel does not significantly affect the efficiency of a boiler system.

H0₂: Air-fuel ratio does not have significant impact on the efficiency of the boiler.

H0₃: Flue gas temperatures do not significantly influence boiler efficiency.

H0₄: Surface heat loss does not significantly affect the efficiency of the boiler.

1.5 Justification of the study

This research strives to establish a boiler EMP in a tea factory. Tea processing factories widely use steam in most of their processes such as withering fermenting and drying and therefore the choice of the plants was informed by the diversity in steam usage. The study evaluates firewood fuel used in the boiler in a bid to determine its effectiveness. Besides this, the economic viability of the commonly used form of energy steam- will be evaluated, and the environmental effect during the production of this form of energy. The study seeks to minimize steam energy losses during production and distribution in the process line to a negligible percentage, improve energy utilization in the plant, and positively impact the control of environmental contamination. Completion of this research and proper implementation will highly benefit the plants in process, production, manufacturing, and hospitality industries as well as domestic facilities that utilize steam. EMP developed in this research provided a simple and unique method for steam energy distribution and utilization as well as environmental conservation measures in industries. Additionally, hugely cuts cost in fuel. Saving in cost by extension increases plant profitability in the long term.

1.6 Significance of the study

The study introduces an energy management method for wood fired boiler aimed at optimizing energy utilization. The proposed approach enhances efficiency while minimizing environmental impact by reducing emissions and controlling pollution levels. Process steam serves as a vital energy source across numerous industrial applications. It supports process heating, cooling, pressure regulation, mechanical drives, component separation, and provides energy for various operations and chemical reactions. Steam's extensive use as an energy medium is attributed to its many benefits, such as low toxicity, easy transportability, high efficiency, superior heat capacity, and comparatively low production costs versus other energy sources.

1.7 Scope of the study

This study focuses on the study of boiler energy stimulated by firewood fuel. Other types of boiler fuel exist namely gas-fired or diesel-fired boilers but the researcher limited to firewood-fired boilers because of their wide application in tea industries. Firewood is cheap and locally available and the technology applied during combustion is simple. In this study moisture in wood fuel, air-fuel and flue gases of the combustion were investigated. Major elements like carbon monoxide, carbon dioxide, Sulphur, and the stack temperatures were considered for analysis. Development of a fuzzy logic system enabled the determination of the optimal levels of the variables under study. Lastly, an EMP was developed to improve efficiency of the boiler which has a significant impact on energy conservation.

1.8 Assumptions of the Study

Assumptions in this research are foundational, unproven beliefs or statements that the researcher accepts as true to conduct the study and interpret its findings. They are

premises upon which the research design and analysis are based. This study is founded on the following key assumptions:

- i) The tea factory under investigation complies with all essential standard operating procedures (SOPs) for boiler operation in steam energy production.
- ii) The key standards related to steam production and efficiency assessment encompass BS 845:1987, ASME PTC-4-1 Power Test Code for steam generating units, and Indian Standard 8793 for boiler efficiency testing. These standards provide the primary guidelines for steam-generating plants.
- iii) Regular annual inspection was done by an authorized expert fully certified by the Directorate of Occupational Safety and Health (DOSH) and therefore this study assumes that regular inspection is done promptly to improve the effectiveness of the system.
- iv) The factory utilized only green villa trees for burning.
- v) The operator of the system is well trained and fully skilled to safely operate, record relevant data, and carry out proper maintenance.

1.9 Theoretical Framework

Theories are developed to explain, advance, predict, and understand a phenomena. Quite often than not theory would aim to challenge and expand upon existing knowledge while remaining within critical bounding assumptions (Anfara, V.A, & Norma, 2015). In this study, the theoretical framework serves as a foundation that supports the research theory. This study is anchored to three theories: the theory of moisture sorption, phlogiston theory, and Lavoisier's theory.

1.9.1 Theory of Moisture Sorption

The theory of moisture sorption elucidates the physical and chemical mechanisms governing the uptake and release of moisture within wood biomass, which predominantly occurs through interactions at the molecular level between water molecules and the wood's porous structure. This process is critical in the context of optimizing wood-fired boiler performance, as moisture content directly impacts combustion efficiency, emissions, and thermal stability. Moisture sorption behavior is typically represented through sorption isotherms, which depict the relationship between equilibrium moisture content (EMC) and relative humidity at a constant temperature. These isotherms are essential for predicting moisture dynamics during storage, handling, and combustion processes.

In particular, Type II sorption isotherms, characteristic of wood, involve multilayer adsorption phenomena where multiple layers of water molecules form on the wood surface. The process is dominated by attractive Van der Waals forces between water vapor and the wood's hydroxyl groups, as well as capillary condensation within the micro and mesopores of the biomass. Understanding these sorption mechanisms allows for better control of moisture levels, which is vital for enhancing combustion efficiency, reducing unburned residues, and minimizing pollutant emissions. Furthermore, the sorption process influences the physical properties of wood, such as dimensional stability, mechanical strength, and thermal conductivity all of which affect boiler operation. Variations in moisture content can lead to issues like slagging, fouling, and incomplete combustion, thereby decreasing overall system efficiency. Therefore, a comprehensive understanding of moisture sorption behavior, including the influence of temperature and humidity fluctuations, is fundamental for designing effective drying and combustion strategies in wood-fired boiler systems. Advanced modeling of

sorption phenomena, incorporating sorption isotherms and kinetics, can inform operational parameters and improve the reliability and sustainability of biomass energy production.

1.9.2 Phlogiston Theory

Boilers utilize combustion technology, wherein fuel is burned in the presence of oxygen to generate heat energy, thereby heating water to produce steam. This combustion results in ash formation, particularly from solid fuels. The phlogiston theory effectively explains the combustion process, the resulting byproducts and the foundational concepts of this research. In early chemical theory, phlogiston was considered a hypothetical principle of fire, believed to be a component of every combustible material, thereby enhancing the efficiency of these materials.

According to this theory, what is currently recognized as oxidation takes place during combustion, resulting in the liberation of phlogiston, which leaves behind a dephlogisticated residue, typically manifesting as ash. Johann Joachim Becher in 1669, suggested that substances contained three varieties of earth: vitrifiable, mercurial, and combustible. He proposed that combustion released combustible earth (Latin: *terra pinguis*, translating to “fat earth”). Consequently, wood was perceived as a fusion of phlogiston and wood ash. The term "phlogiston" was later introduced by Georg Ernst Stahl in the early eighteenth century to denote this theoretical substance. Stahl theorized that the oxidation of metals in air, such as the rusting of iron, constituted a kind of combustion. He suggested that as metals converted into their calx or metallic ash (now identified as oxides), they released phlogiston, thus implying that both phlogiston and calx comprised the essence of metals. Stahl also contended that air served merely to transport the released phlogiston away. Different civilizations have explored and

theorized the nature of combustion, fire, and flame since ancient times, with the Greeks proposing through philosophical doctrines that all combustible materials contained an "Inflammable principle," which was released during combustion to react with air.

The phlogiston theory, which emerged in the 17th century, provided a more extensive framework for understanding combustion. Initially perceived as a metaphysical attribute, phlogiston eventually came to be identified as a physical substance with weight, occasionally attributed a negative weight. Its inadequacies became increasingly evident in the late 18th century as it struggled to clearly explain multiple new observations derived from more precise laboratory experiments. For example, in 1620, the English philosopher Sir Francis Bacon noted the structured nature of a candle flame, while Robert Fludd conducted an experiment showcasing combustion within a sealed container that revealed an air deficit. German physicist Otto von Guericke demonstrated in 1650 that a candle fails to ignite in a vacuum produced by his air pump. Furthermore, in 1665, English scientist Robert Hooke asserted that air contained an active component which combined with combustible materials upon heating to create flames. Additional theories proposed that the temperature of flames was a result of the rapid movements of active air particles and noted that sulfur could ignite in absence of air when mixed with niter, an oxygen-containing compound that promotes combustion.

1.9.3 Lavoisier's Theory

Lavoisier's work is closely linked to thermodynamic principles. Grasping his theory is essential for enhancing boiler efficiency by ensuring effective combustion and heat transfer, all while minimizing energy losses. His emphasis on precise measurements and quantitative analysis is applicable in monitoring and managing parameters within a boiler system, ultimately leading to improved operational performance. Antoine-Laurent Lavoisier made groundbreaking contributions to the understanding of

combustion. In 1772, he discovered that ashes resulting from the combustion of sulfur or phosphorus were heavier than the original substances, leading him to propose that this weight gain was due to a reaction with air. Prior observations indicated that heating metals resulted in lighter metallic ash compared to their initial forms. However, the existence of phlogiston a hypothetical substance once believed to exist within metals—was thought to impart negative weight. Its release during combustion was believed to render the resulting ash heavier than the original metal.

Eventually, Lavoisier identified the "fixed" air that combined with sulfur as identical to the gas produced by scientist Joseph Priestley when he heated mercury's metallic ash. In this light, mercury's combustion could release gas that had previously attached to the metal. This gas was also recognized by Carl Wilhelm Scheele, Swedish chemist as a vital component of air that facilitated combustion, with Lavoisier naming it "oxygen." According to the Lavoisier's theory, combustion occurs when a burning material interacts with oxygen, which is available in limited concentrations in the atmosphere. His theory is built upon several scientific principles, notably the law of conservation of mass, which asserts that the total mass of matter in the universe remains invariant. This principle was initially posited by ancient philosophers and later confirmed in the 17th century. Lavoisier also refined the definition of an "element," stipulating that it cannot be decomposed into simpler substances, thus reinforcing his position.

The soundness of Lavoisier's combustion theory and his novel approach to chemistry, which prioritized the measurement accuracy, gained further validation through the work of English chemist John Dalton on gases and his formulation of the first atomic weight table, alongside contributions from other scientists identifying new gases. The discoveries of nitrogen and hydrogen towards the end of the 18th century, as well as earlier findings related to carbon dioxide and carbon monoxide, bolstered the

reactions, including the recombination of atoms and molecular fragments, as well as the adsorption of reactive particles onto solid surfaces; all are vital components of the hydrogen combustion mechanism. An understanding of the empirical rate constants linked to these processes yields a thorough analysis of combustion characteristics such as explosion limits, ignition delays, and burning velocities.

Carbon monoxide combustion primarily occurs when mixed with hydrogen or hydrogen-containing compounds. The mechanisms involved in these reactions diverge from those of hydrogen combustion, largely due to the rapid interactions between hydroxyl radicals and carbon monoxide. Pure mixtures of carbon monoxide and oxygen (or air) typically ignite only when exposed to high-energy sparks or under elevated pressure and temperature conditions. The exact chemical processes governing their combustion remain inadequately understood, possibly because carbon monoxide oxidation is mainly observed in the presence of hydrogen during the combustion of various natural fuels like wood, coal, and petroleum, which produce carbon monoxide, hydrogen, and related compounds.

The combustion mechanisms of hydrocarbons and other organic materials are yet to be fully elucidated. While many basic steps in hydrocarbon combustion such as those involving hydrogen atoms, hydroxyl radicals, and organic radicals mirror those observed in hydrogen combustion, the overall advancement is complicated by the diversity of molecules and radicals involved. Additionally, oxidation can occur concurrently with thermal decomposition, which breaks down complex organic molecules without oxidation. Hydrocarbon combustion can generally be divided into two types: slow combustion, happening at temperatures below 500 °C and including cool flames seen under particular pressure conditions, and high-temperature

combustion, which is characterized by hot flames. For heavier hydrocarbons, ignition typically progresses in two stages, starting with a cooler flame phase that generates easily oxidizable products before advancing to a hot flame phase.

1.10 Energy management in a processing facility

Energy Management refers to the strategic designing and operation of energy-producing and/or Energy consuming units in an organisation. It entails the systematic, organized, and proactive management of energy utilization within organizations to address both economic and environmental requirements. The primary objectives of energy management in this study are to enhance resource conservation, protect the climate, and reduce fuel costs, while ensuring that consumers have uninterrupted access to the energy they require. Common principles of energy management include: - collecting energy data, monitoring consumption, identifying energy saving opportunities, implementing energy-saving measures, and tracking progress and necessary improvements. In this research, management of energy is viewed as fundamental for achieving energy savings at the various level in an organisation.

Moreover, with the rising demand and declining supply of the non-renewable resources such as coal and gasoline, costs are expected to increase. Additionally, sustainability standards are increasingly stringent due to regulatory pressures. Effective energy management does not necessarily require significant capital investment or complex analyses; it can commence with monitoring and assessing energy consumption patterns over time. This study suggests that making small adjustments to energy consumption behavior can lead to substantial savings. Ultimately, energy management focuses on establishing a foundation of knowledge for informed decision-making to effectively reduce energy consumption.

1.11 Conceptual framework

The conceptual framework consists of the theories relevant to the subject under investigation that shape and inform the research. It illustrates the relationship between the independent variable and the dependent variable. Independent variables are recognized as the causes influencing the research phenomenon, while dependent variables are those that can be explained by the effects of the independent variables (Ravitch & Riggan, 2017). Intervening variables, also known as mediator variables, are theoretical constructs used by the researcher to clarify the relationship between other variables in the study, which typically include both dependent and independent variables. Figure 1.4 presents the conceptual framework and the interconnectedness of these variables.

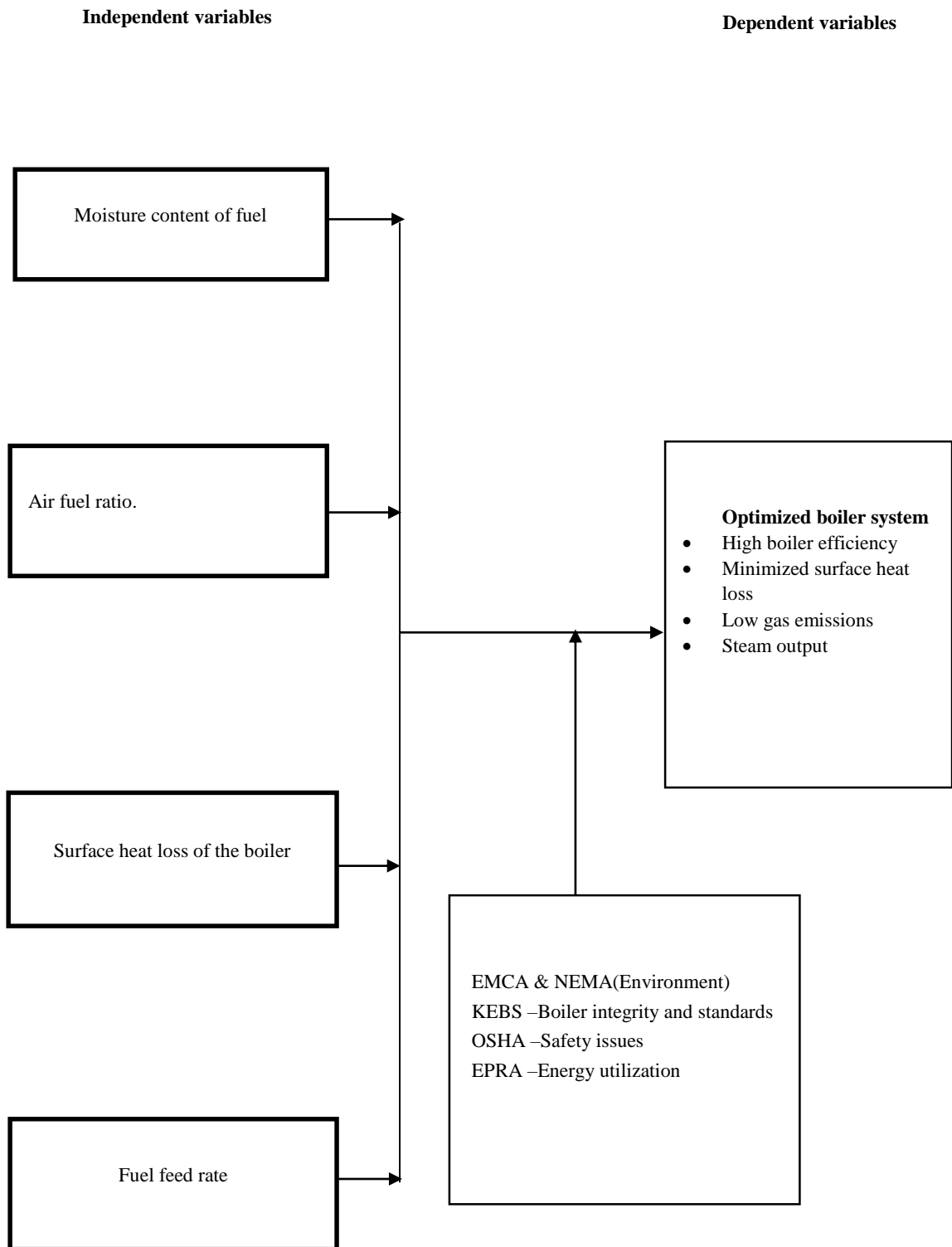


Figure 1.4: Conceptual framework

1.12 Limitation and delimitation

The major limitation of this study was the diversity of fuel used in the boiler system for the production of steam. Three broad classifications of fuels, namely solid, liquid, and gases, exist, and each of them has significant implications on combustion and by extension boiler efficiency (Njeri, 2019). Wood fuel is the most common fuel used in tea-processing boiler systems. Cutting down trees for use in the boiler negates the effort of the government on environmental conservation and this forms a major limitation in this study. Additionally, wood is fed manually in the boiler and therefore automation and determination of fuel consumption rate becomes a challenge. In a boiler system, wood type plays a greater role due to the gross calorific value of energy when burnt creating a variance worth noting for its choice. This formed the basis for the choice of a wood-fired boiler in this study.

1.13 Operational definition of terms

Air Preheater (APH): An air preheater is a device used in boilers to preheat the air required for fuel combustion. This air is supplied by the Forced Draft Fan (FDF).

Boiler: A boiler is equipment designed to heat water or convert it into saturated steam at a specified pressure.

Burner: A burner facilitates the combustion of liquid or gaseous fuels, such as Light Diesel Oil (LDO), Heavy Diesel Oil (HDO), Natural Gas, or LPG.

Combustion: Combustion is an exothermic chemical process that produces fire.

Combustion Chamber: This is a component of a boiler, either inside or external to it, where fuel combustion occurs.

Condensate: During process heating, the steam generated by the boiler releases its latent heat and transforms into water. This water, rich in sensible heat, is referred to as condensate.

Fuel: Any substance that reacts with air in the presence of heat to produce fire is termed fuel. This reaction is known as fuel combustion.

Flue Gases: Flue gases, also known as exhaust gases, are byproducts of fuel combustion. Typically, these include carbon dioxide, carbon monoxide, sulfur dioxide, water vapor, and other compounds. Flue gases result from the reaction of fuel components such as carbon, sulfur, hydrogen, and moisture with air.

Heat Capacity: The heat capacity of a fluid is the amount of heat it can store per unit mass and unit temperature. It is commonly expressed in units such as Kcal/Kg/°C or J/g/K.

Net Calorific Value (NCV): The NCV of a fuel represents the energy stored in it in the form of chemical composition, also referred to as the internal energy of the fuel.

Non-Return Valve (NRV): An NRV is a valve that permits fluid flow in only one direction.

Pressure: Pressure is a critical parameter in boiler design. In the boiler industry, pressure is categorized into three types: design pressure, working pressure, and hydraulic pressure.

Safety Valve: This valve is part of boiler mountings and fittings. Its function is to release excess steam when pressure exceeds the working pressure. As per Indian Boiler Regulations, a minimum of two safety valves is required to ensure human safety.

Waste Heat: Waste heat refers to the heat discharged with flue gases from boilers, furnaces, or kilns. These gases are typically released into the atmosphere via chimneys, resulting in heat losses.

Waste Heat Recovery Boiler (WHRB): A WHRB is a specially designed boiler that recovers waste heat from flue gases. The size and energy output of the WHRB depend on the temperature and volume of the flue gases being utilized.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter deals with a literature review. Close consideration of related literature was utilized in a bid to broaden knowledge on this subject matter. Existing related boiler research were evaluated and the gaps identified formed a strong foundation for this study in order to address existing gaps. This chapter entails a review of related literature with key emphasis on wood fuel moisture content, boiler fuel, boiler insulation integrity, steam formation theory and emissions associated with the steam generation process. Lastly, this chapter provides summary with a critical literature review which links the study to other research work.

2.1 Moisture in Boiler Wood Fuel

Wood is common boiler fuel in tea factories around Kericho in Kenya. Wood in its natural state contain moisture and therefore it requires some treatment before combustion in a boiler. Moisture content in wood typically refers to the water contained within the wood's structure. Moisture in wood is practically expressed as a percentage of the matter of wood's dry weight. Knowledge on moisture content during steam production is important as it determines how efficient steam production process can be improved. The moisture content in the wood depends on several factors such as type of wood, treatment method, and its final processing procedure. When the moisture levels in wood are too high, it can significantly reduce the boiler's efficiency. This increases emissions of harmful gases which can cause operational problems (Kumar et al., 2020).

This piece of research examines how moisture content influences wood fired boiler thermal performance and explores practical mitigation strategies which can guide boiler operators. Proper wood preparation, including the traditional open air drying or mechanical drying methods, is crucial to reduce moisture content before engaging in combustion. Implementing of such measures might help in enhancing boiler efficiency. In addition it minimizes environmental pollution caused by combustion by-products. Key combustion product like carbon monoxide is harmful to human especially if inhaled for a prolonged period of time. Modern tea factories boilers in Kenya are often equipped with sensors that control and provide real-time data. This enables boiler operators to make necessary adjustments and maintain optimal combustion conditions throughout boiler operation period.

This research on energy management plan demonstrates that moisture levels has an adverse effect to fuel combustion efficiency. It also has a long-term health and maintenance costs of boilers. Excess moisture can lead to corrosion and scaling of internal components of boiler system, which degrades performance and results in higher repair expenses (Yang, X et al 2019). In Kericho region where biomass in tea factories is frequently stored outdoors and exposed to unpredictable weather conditions, effective storage techniques and moisture control measures are essential. Solutions such as airtight storage and pre-drying equipment have proven effective in significantly reducing moisture-related issues, thereby making wood-fired boiler operations more sustainable raising the integrity of the process (Jae W. et al 2023). Biomass energy has gained huge prominence in Kenya's tea industry. This calls for deliberate measure to maintain appropriate moisture levels in wood fuel which is critical for enhancing boiler efficiency and supporting environmental sustainability.

2.1.1 Variability in Moisture Content

Studies have shown that green wood has a moisture content ranging from 30% to 60%. Air-dried wood typically has 15% to 25% moisture. Kiln-dried wood has less than 10% moisture. (Jenkins, et al., 2015), noted that the type of wood, cutting season, and storage conditions significantly affect moisture content. Low-moisture wood burns more efficiently, producing more heat and fewer emissions . Mladen B et al (2020),emphasized the importance of pre-drying wood for boilers is crucial to achieving consistent combustion. Higher moisture levels require more energy for water evaporation, reducing net energy output. Jae W. et al (2023) observed that a 10% decrease in boiler efficiency occurs for every 10% increase in moisture content. Incomplete combustion of wood with high moisture levels results in elevated levels of particulate matter (PM) and carbon monoxide (CO) emissions. (Yang, et al., 2019), found that moisture levels above 30% significantly increased unburned hydrocarbons. Wet wood accelerates the formation of tar and creosote in boiler systems, leading to maintenance challenges. Corrosion risks are higher due to the presence of acidic condensation from wet wood combustion.

2.1.2 Measurement and Monitoring of Moisture Content

Oven-drying is the most accurate but time-consuming technique for measuring moisture content in wood. Moisture meters are commonly used for quick field measurements (Mladen B et al,2020).He highlighted the efficacy of capacitance-based meters for wood fuel. Infrared and microwave sensors provide real-time moisture content analysis. A non-invasive technique called Near-Infrared Spectroscopy (NIRS) is being developed for measuring wood moisture levels without causing damage.

2.1.3 Moisture Content Management Strategies

Air-drying is simple but weather-dependent, whereas kiln-drying is faster and ensures uniform drying but requires energy input (Yang, X et al ,2019). He recommended covered, ventilated storage to minimize moisture absorption. Blending high-moisture wood with drier biomass improves combustion efficiency. The use of a suitable mix of dry and green wood has demonstrated improved boiler performance (Veronica K et al 2024.) Use of staged combustion designs and secondary air systems enhances the burning of high-moisture fuels. Incorporation of economizers and superheaters mitigates efficiency losses due to moisture.

2.1.4 Emerging Research Trends

Effective moisture content control in wood fuel is critical for optimizing performance in wood fired boiler. This helps in reducing emissions, and ensuring sustainable biomass utilization. Traditional methods such as air drying and simple storage practices often prove insufficient in maintaining low moisture levels, especially in humid climates. Modern researchers have laid great focus on advanced techniques in managing moisture content. Some innovative time saving and cost effective processes like torrefaction, hydrophobic coatings, and the integration of artificial intelligence (AI) are main areas for modern technology application. Torrefaction, which is a thermal method of wood pre-treatment process is normally conducted at temperature between 200°C to 300°C in the absence of oxygen. This process has gained considerable attention in recent past due to its ability to enhance the energy density and storability of biomass boiler fuel. This process reduces inherent moisture content levels and volatile compounds. Furthermore the process produces properties similar to ones achieved from burning coal. This improves combustion efficiency and reduces transportation costs (Miller et al., 2020). Moreover, torrefaction if properly done in

wood demonstrates improved grindability and increased resistance to microbial decay. It's also more suitable for long-term storage and large-scale energy applications (Branca et al., 2019).

Alongside thermal treatments and surface modification techniques such as hydrophobic coatings in wood, the processes are increasingly employed to prevent moisture absorption during storage. These coatings create a thin layer that employs a barrier that minimizes water ingress into wood from ambient humidity. This process maintains low moisture levels over long periods of time. Studies in this area have shown that application of hydrophobic coatings to wood chips can significantly reduce moisture uptake, leading to more stable fuel quality and consistent combustion behavior (Zhao et al., 2021). This approach is particularly beneficial in regions with high humidity where traditional storage methods face challenges.

This wide application and subsequent incorporation of electronic sensors like AI and machine learning in boilers have opened new avenues for moisture management in biomass systems. By analyzing environmental conditions such as temperature, humidity, and storage duration, AI algorithms can accurately predict moisture evolution in stored wood fuel. These predictive models enable operators to optimize drying schedules, storage conditions, and boiler parameters in real-time. This enhances overall system efficiency and reducing emissions (Li et al., 2022). The integration of IoT sensors with AI in some boiler equipment allows for continuous monitoring, providing actionable insights. Such interventions improve biomass fuel quality control and operational sustainability. Overall, these modern techniques such as torrefaction, hydrophobic coatings, and AI-driven predictive management represent significant

advancements in biomass moisture control. Effective implementation of these strategies is essential for maximizing boiler efficiency, minimizing environmental impacts, and advancing the role of biomass as a renewable energy source in the context of climate resilience and sustainable development.

2.1.5 Global energy trends

The global energy landscape is experiencing a trend towards increased energy consumption, with a notable rise in energy demand. Within this context, the industrial boiler market is experiencing growth due to rising energy needs for heating and steam generation across various sectors. Furthermore, there's a growing emphasis on energy efficiency and sustainability, leading to advancements in boiler technologies and a shift towards waste-to-energy solutions.

From a business perspective, energy efficiency is a sound strategy, as it yields cost savings and improvements through resource optimization and waste reduction. The concept of thermal energy efficiency refers to the ability to get the best results in a given energy related activity by utilizing the least amount of energy resources available (Senthil S et al, 2023). It enables us to reduce the over reliance of any type of energy including the associated environmental impacts. This is applicable from production to consumption of energy. To meet the climate change mitigation targets set by the international community, industries must substantially enhance their energy efficiency. Transition to low-carbon, low-emission technologies, including renewable energy sources is a positive alternative (Harvey, Orvis, & Rissman, 2018). This has sparked a growing interest among researchers to develop more sustainable energy solutions that minimize waste and industrial pollution. This would ensure a more environmentally friendly and efficient energy landscape

2.1.6 Types of wood used for boiler combustion

Wood fuel is a diverse and intricate category of bioenergy source originating from woody biomass. The complex landscape of wood fuels can be segmented into three distinct categories, each playing a pivotal role in the steam energy sector. The first category, primary wood fuels, consists of resources directly harvested from forests, wooded areas, or tree-covered lands specifically for energy production. This includes traditional fuels such as fuelwood, which is often collected from natural forests or managed plantations. Charcoal and ethanol derived from biomass sources also falls in this category. These fuels are typically characterized by their direct origin from living or recently harvested trees. Their availability and sustainability are closely linked to forest management practices and conservation policies (Liu et al., 2020). The second category include, derived wood fuels, and refers to bioenergy byproducts resulting from wood processing activities. These category include sawdust, bark, wood chips, and lignin-rich residues generated during timber processing, paper manufacturing, and other industrial operations. Such byproducts have an advantage in that they utilize waste streams that might otherwise be discarded or burn unintentionally, thereby contributing to waste reduction and energy recovery in industrial settings (Veronica K et al 2024).

The third category is products from repurposed wood fuels. It encompasses wood that is reused or repurposed as a fuel source beyond traditional forestry and industrial contexts. This includes waste wood from construction and demolition sites, discarded pallets, furniture, and other wooden materials that are diverted from landfills and given a new life as biomass fuel. Reusing wood in this manner not only extends the lifecycle of the material but also offers environmental benefits. It's vital in reducing waste and lowering reliance on virgin wood harvesting. In regions like Kenya, where resource constraints and waste management challenges are prevalent, these categories of wood

fuels highlight different avenues for sustainable biomass utilization. They also underscore the importance of establishing proper collection, processing, and regulation systems to ensure the sustainability, safety, and efficiency of wood fuel use across different sectors. Understanding the distinctions among these categories is essential. It enables the development of targeted policies and technological solutions that optimize energy production while conserving environmental resources (Mwangi & Otieno, 2022).

2.1.6.1 Direct Wood Fuels-the Focus of Attention

This topic on direct wood fuels centers on direct wood fuels, which can take various forms and are obtained from forests, including those dedicated to industrial wood production. The availability of direct wood fuel is deeply attached to the overall wood production, serving as a substitute by-product. As industrial wood production increases, so does the quantity of wood fuel become readily available all over the world.

2.1.6.2 Global Statistics and Trends in wood fuels

Wood-fired boilers are a critical component of biomass energy systems worldwide, especially in regions where access to fossil fuels is limited or where renewable energy strategies are prioritized. These boilers are designed to combust various forms of wood fuel, including fuelwood, wood chips, and pellets, to generate heat and, in some cases, electricity. The efficiency and environmental performance of these boilers depend significantly on the type and quality of the wood fuel used and the combustion technology applied. Advances in boiler design, such as improved heat exchange mechanisms, have enhanced the sustainability and economic viability of wood-fired boilers. This has made them increasingly attractive for industrial, institutional, and residential applications in developing and developed nations. (Zhao et al., 2020).

In global levels the use of wood-fired boilers has seen a notable upward trend. This is driven by the rising demand for renewable energy sources. According to recent statistics, industrial biomass boilers account for a significant share of energy produced from biomass, with many facilities utilizing wood residues and processed biomass pellets. For instance, in China and India, the deployment of large-scale wood-fired boilers has expanded rapidly, supported by government policies and incentives aimed at promoting clean energy (Li & Chen, 2021). Additionally, in most of the African countries the adoption of small-scale wood-fired boilers for tea processing factories has increased, offering cleaner and more efficient alternatives to open fires and rudimentary stoves.

Despite these positive interventions, challenges still remain in optimizing the performance and sustainability of wood-fired boilers. Ensuring consistent fuel quality, particularly moisture content and ash levels, is essential for maintaining high efficiency and minimizing emissions. Additionally, the local availability of suitable feedstock influences the adoption and operational costs of these systems. Proper management and technological upgrades are crucial to address issues such as incomplete combustion, particulate matter emissions, and ash disposal. As research continues to improve boiler efficiencies and develop cleaner combustion technologies, wood-fired boilers are expected to play an increasingly vital role in the transition to renewable energy systems, especially in rural and developing regions where biomass remains a primary energy source (Zhao et al., 2020).

2.1.6.3 Emerging Opportunities in Liquid Biofuels

While the conversion of direct fuelwood into liquid biofuels and biogas is currently limited, recent innovations have led to the development of ethanol from lignocellulosic

biomass, potentially paving the way for economic viability in the future (Martinez J et al ,2020). Ongoing research and development are necessary to unlock the full potential of wood fuel and realize its benefits in a more comprehensive manner.

2.1.7 Fuelwood measurement

Most of tea factories in Kenya use wood for boiler fuel. Suryani et al (2022), in their study on the barriers to substituting the firewood with biomass briquette in the Kenya tea industries noted that firewood remains the most economical form of fuel in boilers. In Kenya tea factories measurement of firewood is done in tonnes upon which the price per kilogrammes is dictated by the type of wood supplied. The product is cut into three feet logs and stacked as shown in Fig 2.1 below to allow for a well-controlled and effective drying.



Figure 2.1 Staped fuel wood

(Author: researcher)

Other countries adopt the metric system where fuelwood is often measured and sold in cubic meters ($1\text{m}^3 = 0.276$ cords). Countries like the U.S. and Canada, fuelwood is normally measured and sold by cords ($3.62 \text{ m}^3 = 128 \text{ ft}^3$) which corresponds to a fuelwood pile measuring 4 by 8 feet wide by 4 feet high. In the majority of U.S. states,

cord are legally defined by statute. A “Thrown cord” is defined as a fuelwood pile that hasn’t been stacked and that measures 10 feet long by 4 feet wide by 4 feet high. In a thrown cord, the additional volume is equated to a standard well-stacked cord that has fewer void spaces between individual fuelwood sticks. Fuelwood is also measured and sold in “face cords” which is often not officially defined and may vary from one region to another. The volume of a face cord is approximately a third of a standard cord. Buying fuelwood measured in face cords is not recommended because a face cord is not a legitimately enforceable unit of measurement.

2.1.8 Thermal energy in wood

Fuel contains an amount of energy known as the primary energy in a system which is transformed through combustion which produces final energy for various process applications, such as heating water for domestic and industrial use. Existing standard like International System of Units (SI) specifies that energy is measured in Joules (J), Watt-hours (Wh), and other lesser or higher multiples. The most commonly used units include mega joules per kilogram, mega joules per meter second, and kilowatts per hour per kilogram (Yanchen, 2024)

Table 2.1: Conversion factors of thermal energy units

	Kj	Kcal	KWh	TOE
1 Kj	1	0.239	0.278×10^{-3}	23.88×10^{-9}
1 kcal	4.1868	1	1.163×10^{-3}	0.1×10^{-6}
1 kWh	3.600	860	1	86×10^{-6}
1 toe	41.87×10^6	10×10^6	11.63×10^3	1

(Source:Energy Information Administration- EIA)

Table 2.2: Further conversions

1 kWh	= 860 kcal	= 3.600 kJ (3.6 MJ)
1 MJ	= 239 kcal	= 0.278 kWh
1 kcal	= 4.19 Kj	= 0.00116 kWh
1 toe	= 41.87 GJ	= 11.63 MWh

(Source:Energy Information Administration- EIA)

The Tonne of Oil Equivalent (TOE) is a commonly used measurement unit for comparative and statistical purposes, equivalent to the energy released by burning one ton of crude oil.

2.1.9 Calorific Value

Calorific value, often referred to as heating value, represents the total energy released during complete combustion of a substance, measured per unit volume or mass. However, the moisture content in a fuel, such as wood, negatively affects its calorific value, resulting in a reduction. This is because some of the generated energy is used to evaporate the water, rendering it unavailable for practical thermal applications. It takes approximately 2.44 mega joules (MJ) of energy to evaporate one kilogram of water.

Calorific value (CV) is classified into two primary types: Gross Calorific Value (GCV) and Net Calorific Value (NCV). GCV is determined by measuring the total energy released when a specific quantity of fuel is completely combusted in the presence of oxygen-rich environment within a calorimetric bomb, following the BS1016 test standards. This measurement accounts for the latent heat of vaporization of water produced during combustion, representing the maximum potential energy content of

the fuel (Kumar & Singh, 2020). It is especially useful for evaluating fuels in power generation and industrial applications where the total energy potential is of interest.

In contrast, NCV reflects the usable energy obtainable in practical applications. It is derived under constant pressure conditions, assuming that all water produced remains as vapor in the exhaust gases, and it excludes the energy required to vaporize water. As a result, NCV provides a more realistic estimate of the energy available for heating or mechanical work in typical systems. Generally, unless otherwise specified, the term "calorific value" refers to NCV. For oven-dry wood from various species, the NCV typically ranges from 18.5 to 19 MJ per kg. Conifers tend to have approximately 2% higher NCV than broad-leaved trees, mainly due to their higher lignin, oil, resin, and wax content, which contribute additional energy during combustion. Meanwhile, cellulose and hemicellulose possess lower energy contents, at approximately 17.2–17.5 MJ/kg and 16 MJ/kg, respectively, while lignin has a higher energy density of 26–27 MJ/kg (Chum et al., 2018).

Variability in the anhydrous CV arises from differences in hydrogen content and, more significantly, from ash content, which can influence combustion efficiency and emissions. High ash content can cause slagging or fouling in boilers, reducing performance of a boiler system and increasing maintenance requirements as noted by Perera et al, (2025). For biofuels used in small-scale applications such as tea factories, the anhydrous CV generally ranges between 16.5 and 19 MJ/kg. Wood fuels typically have about nine percent higher energy content compared to herbaceous biomass, primarily due to their higher lignin and resin levels. A critical factor influencing CV is moisture content; ideally, wood fuel should contain no more than 25% moisture. Exceeding this level results in lower combustion temperatures, increased smoke and pollutant emissions, and potential damage to boilers and chimneys. Proper drying and

storage are essential to maximize energy efficiency and minimize environmental impact (Singh & Kumar, 2019).

Table 2.3 Calorific value of wood

Condition of Wood	Water Content(M)	Calorific Value(H)
Fresh timber	50–60%	2.0kWh per kg
Timber stored for a summer	25–35%	3.4kWh per kg
Timber stored for several years	15–25%	4.0kWh per kg

(Source:National Institute of Standards and technology-NIST)

In practice calculation of wood chip requirements in small-medium size plants, the empirical formulas described below are used.

- Boiler capacity in kW x 2.5 = wood chips requirement in bulk m³ per year (softwood P45, M30)
- Boiler capacity in kW x 2.0 = wood chips requirement in bulk m³/year (hardwood P45, M30)

2.1.10 Ash content

Some solid biofuels such as free wood has one of the lowest ash contents, while agricultural biofuels tend to have significantly higher ash content. Utilizing fuels with low ash raises the fusion temperatures and poses a likelihood of ash accumulation on the grate (Perera k et al, 2025).The formation of fusion slag can disrupt combustion by altering primary airflows, increasing overheating of the grate, and contributing to corrosive effects. However, these slag-related issues can be addressed through various methods, such as grate cooling, fume recirculation, and the implementation of mechanical cleaning systems (like self-cleaning screens). For cereal biofuels, calcium additives can also be beneficial.

In terms of melting points, wood bark have relatively high melting points which ranges from 1,300 to 1,400°C, which means they typically do not present significant challenges. In contrast, herbaceous plants have melting points below 1,000°C, making them prone to slag formation during combustion. Cereal grains have even lower melting points, under 750°C, rendering them particularly problematic. For these reasons, agricultural biofuels pose greater challenges in comparison to wood, and should only be utilized in specific selected combustion devices.

2.1.11 Storage of Quality Wood Fuels

The quality of logwood is influenced by tree species, preservation methods, and notably, water content and particle size. Adequate storage conditions are essential for maintaining quality, as logwood should ideally contain no more than 25-30% moisture for household use (Muriuki, 2020). Proper storage techniques can ensure this moisture level is achieved. Our testing of various wood piles in tea factories validated these guidelines, highlighting that the pile's exposure (sunny or shady) is the most critical factor for drying, followed by whether the wood is split or whole, and whether the pile is covered. Logs stored in sunny locations can dry within six months, with split logs drying more rapidly than un-split ones (which still have bark). Conversely, round wood in shaded piles is susceptible to fungal growth if moisture content exceeds 35%. Weather conditions play a more significant role in drying firewood stored in uncovered piles, particularly when the rainy season occurs.

2.1.12 Firewood Storage

For effective drying, wood should be split into smaller pieces. Un-split wood can take up to twice as long to adequately dry. The Springer Handbook of Wood Science and Technology (2023) recommends that the drying area is best when placed in a sunny,

windy location, with wood piles elevated at least 10 cm off the ground to facilitate air circulation and minimize moisture absorption from the ground. Freshly cut wood should not be stored in closed spaces. In such places water cannot evaporate, as this environment favours fungal and bacterial growth, that potentially poses health risks. During Kenya's rainy season, it is advisable to cover wood piles to protect them from rainfall (Mutea & Emily, 2015). Additionally, maintaining a gap that ranges to 10 cm between different wood piles and between the piles themselves and storage walls is crucial for ensuring proper air circulation.



Figure 2.2 Different methods of Wood storage

(Source: Tea processing factory)

The ongoing progress of society is resulting in increased individual comfort, which in turn raises energy consumption across various sectors (Yildiz, et al., 2015). Specifically, tea factories require a dependable and consistent steam supply to facilitate their operations (Songa, 2015). Estimates from BP (2023) indicate that fossil fuels constitutes a range of 80% to 85% of global energy consumption, significantly contributing to boiler gas emissions and to a large extent climate change. Moreover, the reserves of fossil fuels are finite and will eventually be exhausted. Therefore, it is essential to formulate new energy policies aimed at reducing consumption and addressing the environmental impacts associated with fossil fuel dependency.

In steam fuel context biomass offers a clean energy alternative that can help mitigate this reliance. Lazik (2020) points out that more than 230 billion tons of biomass annually are produced, with 24% used for basic needs and industrial applications, leaving 76% available for potential sustainable use as a "green" carbon source in industrial economies. However, the energy sector faces obstacles regarding the efficient storage of large quantities of biomass fuel. Biomass resources are often widely dispersed and possess lower energy densities (Craven et al., 2015). To enhance their energy value for large-scale applications, biomass must undergo pretreatment, which includes processes like cutting, drying, and compressing (Wei-Hsin et al., 2015). Furthermore, Mureithi (2020) emphasizes that improving storage of this useful resource is critical for maintaining biomass quality, particularly in tropical climates where high humidity can affect fuel usability. Similarly, Ndung'u (2019) discusses how effective storage techniques can mitigate losses during transportation and storage, ensuring a reliable supply of biomass for energy production.

Options in creating effective methods for biofuels through densification provides products that are easier to transport, handle, and store while ensuring they meet high commercial quality standards. Densified biomass fuels, such as pellets, are increasingly advantageous due to their cost-effectiveness in transport, storage, and handling compared to other forms of biofuels (Tauro et al., 2018). The International Energy Agency (IEA, 2021) notes that pellets are not only easy to process but can also be transported over long distances with relatively low safety risks. Wood pellets represent a valuable biomass energy source, particularly important given that fossil fuels are significant contributors to CO₂ emissions (Thomson et al., 2015). They combust cleanly, emitting fewer air pollutants; Kowollik (2014) emphasizes their carbon neutrality relative to other heating methods. Additionally, Wanjau (2020) highlights that the

implementation of pellet technology in Kenya can significantly reduce reliance on traditional fuels, fostering a shift towards more sustainable energy practices. Many experts recommend that if renewable energy development continues at its current pace, by 2050 these sources could account for roughly 30% of the world's energy needs, with wood pellets being instrumental in this energy mix (Guo et al., 2015).

Economically, wood pellets are generally more affordable than fossil fuels such as oil, liquefied petroleum gas, and electrical systems, primarily due to their higher GCV content, (Thomson et al., 2015). Furthermore, wood pellet production can be financially beneficial because the raw materials are typically inexpensive, and tea factories can utilize trees from their own properties (Obiri, 2020). The accessibility of these materials and the stable pricing of raw inputs provide a significant advantage over the price volatility associated with fossil fuels (Roh, 2016). According to Veronica K et al (2024) utilizing local resources not only supports fuel security but also promotes rural development through job creation in processing facilities. In addition, they observed that local production of wood pellets can contribute to energy security and economic resilience by reducing dependence on imported fossil fuels.

Wood reaffirmed as an essential energy source, aligns with current energy requirements and is supported by existing research, making it an especially appealing option during economic downturns, as noted by Lazik (2020). This results to wood pellets as a viable and sustainable energy alternative, as highlighted by Pierobon et al. (2015) .Bringing additional benefits such as fostering local economic growth and job creation. Finally, Mwangi (2017) emphasizes the importance of involving community creating awareness in promoting the adoption of biomass technologies. This can drive acceptance and integration into local economies. This has led to a growing demand for wood pellets in

Kenya, sourced from a variety of biomass materials, including wood waste. Pelletizing also offers a practical solution for reducing the excess waste generated in boiler plants.

For tea factories in Kenya, the predominant use of wood pellets necessitates an initial evaluation of their fuel properties against established standards. This assessment will ensure consistency, minimize waste, and enable a steady supply of biofuels that meet usage requirements. The mechanical, physical, and chemical properties of the pellets are crucial factors influencing their quality and efficiency. Therefore, this study aims to evaluate and characterize various commonly used wood to assess their suitability for steam production in accordance with international standards and specific user requirements in heating systems.

2.2 Air-Fuel Ratio in a Boiler System

This is the ratio of the mass of air to the mass of fuel being burned in a boiler system. The air-fuel ratio (AFR) in wood-fired boilers plays a pivotal role in optimization process. Proper management of AFR ensures complete combustion of the biomass fuel, minimizing unburned residues and maximizing thermal energy output. Recent advancements in sensor technology and automated control systems have facilitated more precise regulation of air fuel ratio. This has led to significant improvements in energy efficiency and environmental compliance. In the context of tea factories, where biomass remains a primary energy source, optimizing AFR is crucial for sustainable energy utilization. Mwangi (2017) highlight that if properly implemented intelligent control systems in Kenyan wood boilers can increase efficiency by up to 15%, reducing fuel consumption and emissions.

Furthermore the interplay of factors influencing AFR such as fuel moisture content, biomass particle size, and combustion chamber design should not be ignored.

Variations in moisture content, common in Kenyan biomass due to storage conditions variability in weather condition, can lead to incomplete combustion and higher emissions if not properly managed. Recent research by Otieno et al. (2022) emphasizes the importance of pre-drying biomass and employing adjustable air supply mechanisms to maintain optimal AFR across different fuel categories. Incorporating these strategies into energy management practices not only improves boiler performance but also supports Kenya's national objectives of increasing renewable energy contribution and reducing reliance on fossil fuels. The integration of real-time AFR monitoring and adaptive control algorithms is thus vital for achieving sustainable and efficient biomass energy systems within the Kenyan context.

2.2.1 Importance of Air-Fuel Ratio in a Boiler

The air-fuel signifies the mass ratio of air to fuel in the combustion process. A stoichiometric ratio guarantees complete combustion, maximizing energy output and minimizing emissions. However, boiler systems often function with air-fuel to accommodate variability in fuel characteristics and air distribution (Waweru, 2020). Optimal levels of air-fuel typically range from 15% to 25%, ensuring thorough combustion while preventing heat losses attributed to excessive air supply. An improper AFR can result in incomplete combustion, thereby generating pollutants such as carbon monoxide (CO) and unburned hydrocarbons (Babatunde et al., 2021).

The air-fuel ratio (AFR) greatly influences combustion efficiency and emission levels in boiler operations. When the AFR is too low, the mixture becomes fuel-rich, leading to incomplete combustion, higher CO emissions, and increased formation of soot and particulate matter. Conversely, excessively high AFRs mean more excess oxygen, which can lower flame temperatures, reduce thermal efficiency, and result in

unnecessary heat loss (Kumar et al., 2019). Maintaining an optimal AFR is therefore crucial for balancing complete combustion with energy efficiency and environmental compliance. Proper control mechanisms, such as automated blowers and oxygen sensors, are often used to monitor and adjust AFR in real time for optimal performance. Furthermore, the control of AFR impacts the longevity and maintenance requirements of boiler systems. Excessive air increases the volume of flue gases and can accelerate corrosion due to higher oxygen levels in the exhaust, while insufficient air can cause soot buildup and incomplete combustion, damaging burners and heat exchangers over time (Singh & Patel, 2021). Proper calibration and consistent monitoring of AFR not only improve combustion efficiency but also extend equipment lifespan and reduce operational costs. Recent advancements in sensor technology and automation have facilitated more precise control of air-fuel mixtures, contributing to cleaner and more sustainable boiler operations (Liu et al., 2020).

2.2.2 Factors Influencing AFR

High moisture content in wood fuel reduces combustion temperatures and increases the demand for primary air in drying wood. According to Yang, X et al (2019) optimal combustion occurs when wood moisture content ranges between fifteen to twenty five percent. The size of the fuel particles also affects combustion efficiency: Smaller particles burn more quickly but may require increased air velocity to prevent clogging or ash accumulation. Air staging dividing the air supply into primary, secondary, and tertiary streams. This enhances combustion efficiency and lowers emissions. Primary air fuel pyrolysis and char combustion, secondary air combusts volatile gases released during pyrolysis, and tertiary air ensures complete oxidation of residual gases. Benson K et al (2024) alludes that adhering to emissions standards necessitates maintaining

precise AFR, as proper ratios minimize the release of particulates, NO_x, and CO, which is a regulatory requirement established by the environmental regulators like NEMA. Regulatory bodies such as the NEMA have introduced policies, including Method 28A, which details procedures for measuring air fuel ratio (AFR) and ensuring that boiler systems comply with emission limits.

2.2.3 Air-Fuel Control in a Boiler

Table 2.4 presents the theoretical air requirements for the combustion of various fuels. In practice, air-fuel is necessary for the boiler complete combustion, adjustment for variations in combustion conditions, and maintain optimal stack performance for certain fuels. The ideal level of air-fuel to maximize boiler efficiency is achieved when minimizing losses from incomplete combustion and the heat carried away by flue gases. This optimal level is influenced by factors such as furnace design, burner type, fuel characteristics, and process conditions. Testing different air-fuel ratios is essential for determining effective AFR levels for enhanced boiler performance.

Table 2.4: Data for theoretical Combustion in ideal Boiler Fuels

Fuel	kg of Fuel Required per kg of air	kg of air Gas per kg of Flue gas	m ³ of fuel Gas per kg of Flue gas	Theoretical %CO ₂ in Dry Flue Gas	Practical %CO ₂ % in Flue Gas
Solid Fuels					
Wood	3.2	3.43	2.61	20.65	10-12
Lignite	4.6	5.63	4.58	19.80	14-15
Bagasse	10.8	11.7	9.40	18.70	10-13
Paddy	5.8	6.4	4.79	20.3	11-13
Coal (bituminous)	8.4	9.10	6.97	19.40	9-13
Liquid Fuels					
LSHS	14.04	14.63	10.79	15.5	9-14
Furnace Oil	13.90	14.30	11.50	15.0	9-14

(Source:National Institute of Standards and technology-NIST)

Optimizing air-fuel levels can significantly reduce flue gas losses. For every 1% decline in air-fuel, efficiency can increase by about 0.6%.

The study explores various techniques for controlling air-fuel. Portable oxygen analyzers and draft gauges provide periodic measurements, enabling operators to manually adjust airflow for improved performance. Continuous oxygen analyzers, with local readouts and draft gauges, allow for real-time monitoring and fine-tuning of airflow, further improving efficiency. More advanced systems feature continuous oxygen analyzers paired with remote-controlled pneumatic damper positioners, offering centralized control over multiple firing systems. The most difficult approach, automatically controlled stack damper, automates airflow adjustments and is cost-effective for large-scale operations.

Table 2.5: Level of air Requirement for Various Fuels

Fuel Type	Air-fuel (% by weight)
Pulverized Coal	15-25
Coal	30-60
Fuel Oil	14-20
Wood	18-25
Natural Gas	6-7
Bagasse	25-30
Black Liquor	30-45

(Source: National Institute of Standards and technology-NIST)

2.3 Flue gas emission in a boiler system

Flue gas emissions in boilers result from the combustion of fuel, where chemical reactions release heat, generating various gaseous and particulate byproducts. This research study strives to review theory behind flue gas emissions which is critical for optimizing boiler performance, reducing environmental impact, and ensuring compliance with regulatory standards.

2.3.1 Composition of Flue Gas

Combustion is characterized as a chemical reaction in which combustible elements of fuel are oxidized, releasing a substantial amount of energy (Paraschiv et al, 2020). In a wood-fired boiler, the burning of fuel generates hot gases, which serve as the primary heating medium. This process is exothermic, consuming both fuel and air, and produces combustion gases along with solid by-products like slag and ash (Paraschiv et al, 2020)..Fuels are defined as materials that generate heat through combustion and must fulfill several criteria to qualify. Firstly, they must react exothermically with oxygen at

high speed and temperature. Secondly, the combustion by-products should be non-toxic to minimize air pollution control systems and CO₂ capture. Thirdly, the fuel must be readily available naturally and cost-effective, particularly in the tea industry. Lastly, the combustion products must be corrosive to exposed surfaces, a requirement that should be met by implementing a sulphur oxide reduction system. Solid fuels, like firewood, have varying proportions of oxygen, carbon nitrogen, hydrogen, sulphur, moisture, and ash, complicating precise mass analysis.

The main components of any solid fuel are the combustible mass, which refers to flammable materials, and ballast, which consists of ash and slag. To accurately calculate the weight of each component (in kg of component/kg of fuel), understanding the elemental chemical composition is crucial. Sulfur is undesirable as it can react with moisture in flue gas, forming corrosive sulfuric acid that damages the metal components of the combustion system. Since air is readily available, it is primarily used for oxidation during fuel combustion. Oxy-fuel combustion technology, which replaces air with a mixture of oxygen and combustion gases in the cycle, is a promising method for reducing CO₂ emissions and capturing CO₂ (Xiang.L et al, 2021). Different types of combustion produce various combustion gases, detailed in the table below:

Table 2.6 Types of combustion

S/No.	Type of Combustion	Gases Produced
1	Incomplete combustion	CO, CO ₂ , SO ₂ , H ₂ O, and N ₂
2	Theoretical / Stoichiometric combustion	CO ₂ , SO ₂ , H ₂ O, and N ₂
3	Air-fuel combustion	CO ₂ , SO ₂ , H ₂ O, N ₂ , and O ₂

Generally, a suboptimal air-fuel lead to significant loss of energy and increased air pollution emissions (Dong, Fang, & Jingqi , 2018). The buildup of CO₂ emissions

impacts the climate and primarily contribute to the greenhouse gases effect (Zhu et al., 2022). The Kyoto Protocol and the Paris Agreement aim to mitigate greenhouse gas emissions under the United Nations Framework Convention on Climate Change (UNFCCC), with CO₂ identified as a crucial greenhouse gas requiring reduction or recycling (Xiang.L. et al, 2021)

Numerous research has analysed emissions from flue gas across various facilities, such as the work by (Ciobanu.C.et.al., 2022), which aimed to assess the emissions of pollutants (total flue gas and dust: NO_x, CO and SO₂) at boiler chimney outlets. Their findings indicated that co-incinerating waste proved to be more environmental efficient and that acidic gases could be neutralized with an oven heat exchanger. Zhu et al. explored mitigating impact of NH₄HSO₄'s on selective catalytic reduction (SCR) catalysts at lower temperatures in tea industrial settings. (Golachowska.K.et. al, 2022) Conducted laboratory studies on CO₂, NO_x, and SO₂ emissions from biomass combustion and emissions from a coal generated plant and concluded that there is lower concentrations compared to coal, highlighting its unique role as a renewable energy source. Kamau and Muthui (2021) suggest that effective modeling of flue gas cleaning technologies is crucial for environmental sustainability.

In related research, Dong et al. (2020) modeled twelve scenarios for available cleaning technologies in flue gas and found that a dry system of sodium bicarbonate and selective non-catalytic reduction (SNCR) was the optimal choice in reducing climate change impact (37.1 kg carbon dioxide equivalent/t MSW), where wet systems had greater effects than dry alternatives. Dal Pozzo et al. (2018) examined technologies for removing acid gases, aiming to identify superior designs for dry, semi-dry, and wet systems, discussing each alternative's benefits and limitations from environmental and

economic considerations. (Mungai. E.et.al, 2020) analysed the use of dolomitic sorbent in high temperature in treating acid gases, focusing on sodium bicarbonate (NaHCO_3) for drying typical acid gases, identifying the reagent's production and solid residue treatment as key environmental considerations. Overall, research on flue gas emissions and cleaning systems remains a critical and ongoing topic, closely linked to environmental and climate issues.

2.3.2 Waste heat recovery from flue gases

Waste heat recovery in a wood fired boiler involves deliberate capturing and reusing heat that would otherwise be lost, typically from flue gases or other industrial processes, to generate additional steam or hot water. With the rapid industrial growth, energy consumption has been rising sharply, leading to the swift depletion of wood-based energy resources. To maximize the benefits from these diminishing resources, prioritizing waste heat recovery from processes such as burning wood as boiler fuel is essential. Waste heat recovery provides both direct and indirect benefits. Direct benefits include lower fuel consumption and cost, while indirect benefits include reduced environmental pollution (Terhan. M.et.al, 2016).

Enhancing energy efficiency is essential, and this can be achieved through various measures. These include optimizing fuel combustion within existing systems, maximizing heating efficiency, recovering waste heat, improving the conversion of heat into work, reducing emissions of air pollutants, and minimizing the use of energy resources that have detrimental environmental impacts (Aleksandrs. A, 2019).

Waste heat is the thermal energy released by a boiler as flue gases at temperatures higher than the ambient environment, which can be captured for further use. The composition of flue gases significantly influences heat loss, which may stem from latent

heat in dry flue gases devoid of water vapor, heat in hot water vapor, and products of incomplete combustion such as CO, soot, and unburned fuel. Aleksandrs A (2019), highlighted that boilers typically lose about 20% of the combustion energy through flue gases; however, nearly 50% of this energy loss can be recovered depending on the specific operating conditions. By recovering both sensible and latent heat from flue gases, the thermal efficiency of boilers can be enhanced. Gas-fired systems are often favored since the condensation from natural gas combustion is less corrosive compared to other fuels, and the combustion products contain more moisture (Terhan. M.et.al, 2016)).

In a study by (Cong. C.et.al, 2021), a steam pump system featuring a gas condenser, air humidifier, and gas-water heat exchanger was evaluated. The exhaust flue gas temperature decreased from 80°C to 30.9°C, resulting in an efficiency improvement of over 10%. Heating the air to above 50°C also reduced NO_x concentrations from 33 ppm to 24.6 ppm, which is a reduction of approximately 25.4%. Yang, X et al (2019) proposed a gas-fired absorption heat pump designed to recover high-order sensible heat and low-order latent heat from flue gases.. Their system was able to provide nearly 50 kW of district heating, which is especially advantageous for colder regions.

Additionally, (Cong. C.et.al, 2021) introduced a system that captured residual heat in sulfur-reduced flue gas using direct contact heat transfer and absorption technologies. This system effectively lowered the flue gas temperature and recovered waste heat with the help of low-temperature water from a heat pump, which was then used to heat the return water in mains Systems.

While it is important to keep stack temperatures as low as possible, they should not fall to levels that allow water vapor to condense on the stack walls, particularly when

burning fuels containing sulfur, as this can result in sulfur dew point corrosion. Stack temperatures above 200°C may indicate the potential for waste heat recovery and could suggest a need to clean heat transfer and recovery equipment to prevent scaling (Cong. C.et.al, 2021).

2.4 Surface Heat Loss in a Boiler

Surface heat loss in a boiler primarily occurs due to heat transfer from the exposed surfaces of the boiler to the surrounding environment. This form of heat loss is significant because it accounts for a considerable portion of the total energy inefficiency in boiler operations. The heat transfer mechanisms involved include conduction, convection, and radiation, which are influenced by factors such as surface temperature, material properties, and environmental conditions (Kumar et al., 2020). Uninsulated or poorly insulated surfaces tend to facilitate higher heat dissipation, leading to increased fuel consumption and operational costs. Therefore, understanding and managing surface heat loss is crucial for optimizing boiler efficiency and reducing operational expenses.

Surface heat loss in a boiler depends on the size, design and operational parameters. Large surface areas such as furnace walls and superheaters tubes are more prone to heat loss by radiation. (Zhou et al., 2020). Emissivity of the surface material affects the extent of radiative heat transfer. Materials with higher emissivity radiate more heat. Environmental factors such as ambient temperature and wind speed can further exacerbate heat losses by increasing convective heat transfer. Consequently, advanced monitoring and control strategies are essential to identify areas with excessive heat loss and implement corrective measures effectively.

Perera k et al (2025) in their study on decision making criteria for boiler maintenance observed that the maintenance and condition of the boiler surface play a pivotal role in surface heat loss. Proper maintenance ensures efficient heat transfer, minimizes heat leaks, and prevents issues like scale and deposit buildup that hinder heat exchange. Neglecting maintenance can lead to decreased efficiency, increased fuel consumption, and higher operating costs. Regular inspection and cleaning of boiler surfaces can mitigate such issues, thereby reducing heat losses (Li et. al., 2021). Modern thermal insulation materials and techniques also contribute to minimizing heat transfer to the environment. Overall, reducing surface heat loss involves a combination of proper design, maintenance, and operational adjustments to ensure heat is retained within the system for productive use.

2.4.1 Mitigation Measures for Surface Heat Loss

Insulation is the most effective measure to mitigate surface heat loss in boilers. High-quality thermal insulation materials like ceramic fibers, mineral wool, or foam-based insulations reduce heat transfer from the boiler surfaces to the environment (Wang. et. al., 2020). Installation of insulation including sealing joints and preventing thermal bridging, enhances the overall effectiveness of surface heat control. Additionally, adopting reflective coatings on boiler surfaces can reduce radiative heat losses by reflecting infrared radiation back into the system, which improves energy retention (Chen et al., 2020). One more critical mitigation strategy involves optimization of boiler operating conditions. Maintaining appropriate surface temperatures and controlling combustion processes help minimize unnecessary heat dissipation (Kumar et al., 2020). Implementing advanced control systems and real-time monitoring can detect anomalies such as excessive heat Moreover, regular maintenance routines, including cleaning and

repairing corrosion or fouling, ensure that the surface conditions remain optimal, thus limiting heat loss (Li et al., 2021).

Innovative technologies such as regenerative heat exchangers incorporated in the boiler system can also be used to recover heat that would otherwise be lost through the surfaces. These systems capture waste heat from flue gases or other parts of the boiler and reuse it to preheat incoming feed water or combustion air, thereby improving overall thermal efficiency (Zhou et al., 2020). Integrating these features into boiler design and operation not only reduces surface heat loss but also contributes to sustainable and cost-effective energy use in industrial processes. Combination of the insulation, operational optimization, and advanced heat recovery technologies offers a comprehensive approach to mitigating surface heat losses in a boiler system.

2.5 Boiler Efficiency

Efficiency is a measure on how a boiler works. Deteriorating efficiency is a sign of a failing boiler. Energy efficiency measures how effectively the energy in the fuel is utilized (Chen, 2021). Given the substantial energy used in steam production process therefore enhancing boiler energy efficiency can result in considerable savings. In tea production, for example, applying Best Available Technologies (BAT) can boost energy efficiency by 5% to 33%. The frequency of efficiency assessments and the specific type of efficiency calculation employed may vary based on the criticality of boiler in a production process.

Review of existing literature indicates a focus on addressing particular challenges. Barma et al. (2017) examine the relationship between boiler energy efficiency and the energy sector's environmental impact, noting that improved efficiency can significantly

reduce fuel consumption and CO₂ emissions. Savargave and Lengare (2018) compared various artificial intelligence (AI) methodologies, although a comprehensive overview of all methodologies was not presented. A mathematical consolidation of these methodologies offers better insight into the most suitable options for specific applications. Boiler efficiency is perceived as the ratio of energy contained in the steam to the energy held in the boiler-feed water, expressed as a percentage of the energy in the fuel. It can be computed by subtracting all heat loss components from 100%. The primary advantage of this heat loss method is that measurement errors do not significantly impact the determination of boiler efficiency. Major heat losses in a boiler arise from dry flue gases, moisture and hydrogen in the fuel, moisture in the combustion air, incomplete combustion, and other unaccounted losses. Minimizing these heat losses can improve boiler efficiency.

Munir et al. (2020) assessed a wood-fired boiler with a steam generation capacity of 60 tons per hour at a pressure of 23 kg/cm² and a temperature of 350 °C, recording an efficiency of 77.86% based on the net calorific value with 50% wood moisture content. Efficiency calculations using both methods were analyzed and compared, revealing significant differences. The efficiency derived from the higher heating value (HHV) highlighted the influence of wood moisture, which was not as apparent with the net calorific value. Additionally, Platvoet, E., (2020) found that the temperatures of exhaust gases and feed water significantly impacted boiler efficiency. He furthermore noted that controlling the levels of air-fuel supplied to the boiler can yield substantial improvements in efficiency. Although much research has been conducted to evaluate boiler efficiency and the factors influencing it, additional investigations are necessary for a precise quantification of these phenomena. A comprehensive analysis of heat

losses, stack temperature, ambient temperature, and air-fuel is vital for effective energy optimization. Consequently, this study aims to establish optimal operational conditions for wood-fired boilers and develop an energy management plan.

2.6 Optimization theory

This study utilizes process optimization which involves the implementation of structured methods, strategies, disciplines, and tactics to improve a specific process within the parameters of a project or initiative. Key considerations during optimization, as alluded to by Mwangi (2017), include firstly determining the objective functions. This is the function to be minimized or maximized. Secondly establishing the decision variables which the researchers control to get optimal solution. Thirdly is determining the constraints which are limitations or restrictions on the decision variables and finally feasible region must be set. Feasible region is a set of all possible solutions that satisfy the constraints. The optimal solution lies in this region.

There are many ways in which a process can be adjusted so that it objectively functions better than it did. Taking out a step, removing a step, or rewriting a step in the process are all simplistic examples that can help streamline a work-flow in a steam system. Generally, a process is defined and optimization is implemented as a composite of steps, including the input process and output stages in steam production which must be matched properly. The next step is to operate the equipment efficiently through best practices in operation and maintenance as well as judicious technology adoption. Park et al. (2022) proposed numerous strategies in optimizing system performance, including eliminating steam leakages through trap improvements, maximizing condensate recovery, implementing combustion controls to enhance combustion efficiency, and replacing energy-intensive equipment such as air compressors, pumps, fans,

refrigeration compressors, heaters, furnaces, and boilers, where substantial energy efficiency improvements are achievable.

2.6.1 Air fuel ratio in a wood fired boiler system

Achieving complete and efficient combustion in a boiler system is critically dependent on maintaining an optimal air-fuel ratio. The air blowers integrated into boiler systems play a vital role in this process by introducing turbulence within the firebox, which promotes thorough mixing of air and fuel. Proper mix and fuel turbulence ensures more complete combustion, thereby maximizing heat transfer efficiency and reducing pollutant emissions. Blowers in boiler serve to prevent overheating and potential damage to boiler tubes by controlling the temperature within safe operational limits. As boiler loads fluctuate due to varying energy demands, the mixture of fuel and air must be continuously adjusted to sustain optimal combustion conditions. This underscores the importance of real-time monitoring of the combustion process (Kumar & Singh, 2021).

Monitoring and controlling the air-fuel ratio involves assessing the levels of specific combustion gases, primarily oxygen (O_2), carbon monoxide (CO), and carbon dioxide (CO_2). These gases serve as indicators of combustion completeness; for instance, low oxygen levels typically suggest that the fuel is being burned efficiently. High CO levels in combustion process may indicate incomplete combustion. Precise measurement of these gases allows operators to fine-tune air input, thereby reducing air-fuel and minimizing fuel consumption while maintaining desired thermal output (Nikula et al., 2016). The optimal ratio not only enhances energy efficiency but also reduces the formation of harmful pollutants such as NO_x and particulate matter, contributing to cleaner combustion processes. Sensor technology have enabled more accurate and real-time monitoring of combustion gases, facilitating dynamic control of the air-fuel

mixture (Zhao et al., 2022). Implementing advanced control systems based on these measurements can significantly improve boiler performance. Additionally, optimizing the air-fuel ratio is vital for achieving compliance with environmental regulations. As research continues to evolve, integrating intelligent control algorithms and predictive modeling offers promising avenues for further enhancing boiler efficiency and reducing the environmental footprint of biomass and fossil fuel-based systems (Liu & Wang, 2022)

2.6.2 Fuzzy Logic Optimization

Fuzzy logic emerged in the 1960s through the groundbreaking work of Lofty A. Zadeh, who introduced the concept of the “principle of incompatibility.” This innovative framework allows for the representation of fuzzy sets, which are collections of elements characterized by varying degrees of membership. Each fuzzy set is defined by specific membership functions that assign values ranging from 0 to 1, reflecting the extent to which an object belongs to that set. One of the key benefits of using fuzzy logic is its alignment with human reasoning, which often evaluates truth or falsity in relative terms rather than absolute categories. Instead of simply categorizing responses as "YES" or "NO," fuzzy logic accommodates a spectrum of possibilities, using linguistic terms such as “slightly,” “mostly,” “more,” and “less” to indicate levels of association (Etienne E & Mordeson, 2018). This approach mirrors the complexity of human decision-making, capturing the gradations of belief and uncertainty that exist in real-world situations.

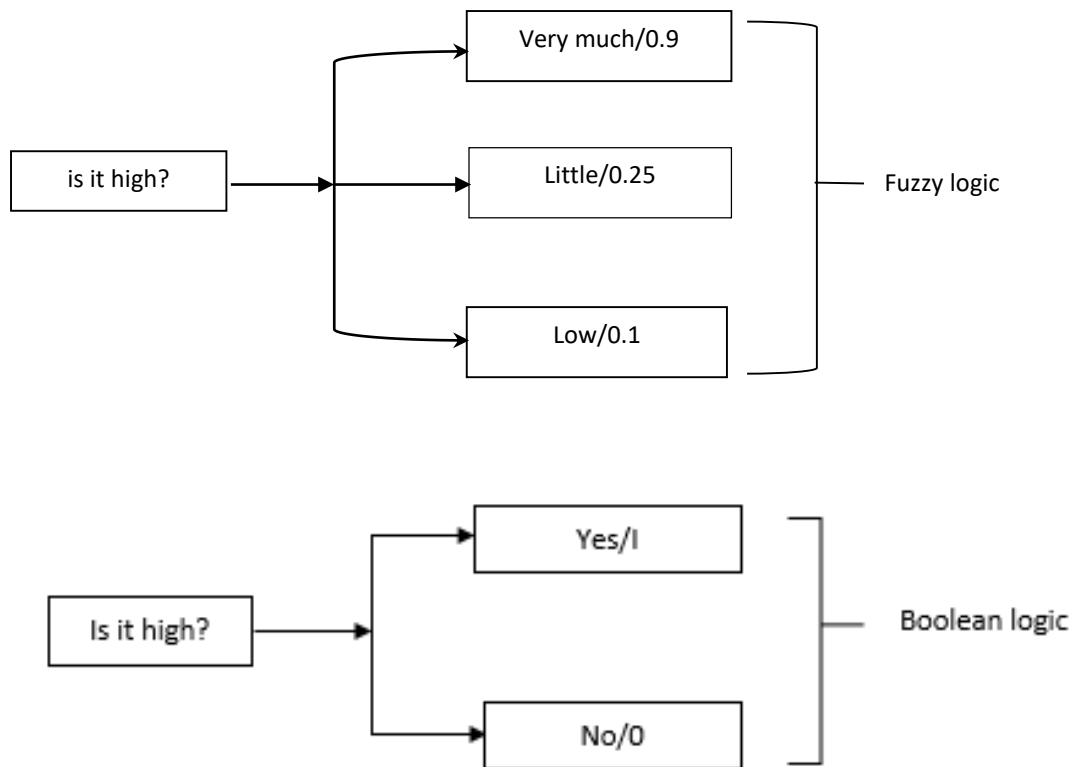


Figure 2.3 An outline of Fuzzy logic optimizations

Fuzzy logic functions by evaluating the spectrum of input possibilities to produce a specific output. It is applicable to systems of different scales and capabilities, ranging from microcontrollers to larger networked or workstation-based systems. Additionally, it can be implemented in hardware, software, or a combination of the two.

2.6.3 Fuzzy Logic Architecture

Fuzzy logic in this research provides an effective approach for controlling wood fire boilers by managing the complexities associated with biomass combustion. This study outlines a systematic process to design and implement a fuzzy logic control system tailored to optimize combustion efficiency, minimize emissions, and improve overall boiler performance. The fuzzy logic architecture utilized in this research comprises four primary components .

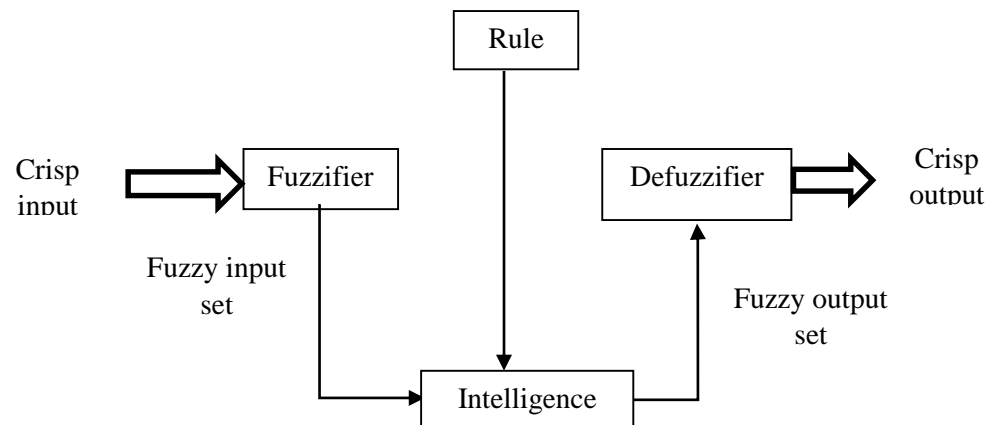


Figure 2.4 Fuzzy Logic architecture

2.6.3.1 Rules

This aspect incorporates all rules and conditional statements as specified by experts, aiding in the decision-making process. It involves constructing the fuzzy rule base, which consists of IF-THEN rules derived from expert knowledge and empirical data.

For instance:

- IF fuel moisture is High and temperature is Low THEN efficiency is low.
- IF air supply is Low AND temperature is Medium THEN efficiency is moderate.

This rule base serves as the decision-making core of the fuzzy logic system, creating a framework for controlling the boiler's operations based on changing inputs (Zhang, C et al,2025).Recent advancements in fuzzy theory have yielded various efficient methods for designing and optimizing fuzzy controllers, often leading to a decrease in the number of fuzzy rules required.

The development of adaptive fuzzy rule bases has further enhanced the flexibility and robustness of control systems in boiler operations. Adaptive fuzzy systems can modify their rule sets in real-time based on evolving process conditions and data patterns, thus maintaining optimal performance and efficiency (Chen et al., 2020). Moreover, integrating machine learning techniques with fuzzy logic has facilitated the automatic

generation and tuning of rules, reducing reliance on manual rule formulation and improving system responsiveness (Li & Wang, 2021). These innovations contribute to more intelligent, reliable, and adaptable boiler control systems, capable of handling complex and dynamic operational environments.

Furthermore, the formulation of rules must also consider safety and environmental regulations to prevent hazardous operating conditions. For example, rules can be designed to automatically reduce fuel input or increase exhaust venting if emissions exceed permissible limits, thus ensuring compliance and safety (Zhang & Liu, 2021). Incorporating such safety-oriented rules into the fuzzy control framework helps in achieving sustainable and environmentally friendly boiler operations, aligning with global standards and policies

2.6.3.2 Fuzzification

The design process continues with the selection of an inference mechanism. The Mamdani inference method is often preferred for control applications due to its intuitive rule structure. This mechanism evaluates the fuzzy inputs against the rules in the rule base and generates fuzzy outputs. During this process, the system aggregates the results from all applicable rules to derive a comprehensive output (Khan & Qureshi, 2022). This step involves transforming inputs or crisp numerical values into fuzzy sets. Crisp inputs can be measured using sensors and subsequently sent to the control system for further processing. The input signal in this study is divided into five categories as shown in the figure 2.5.

LP	Large Positive
MP	Medium Positive
S	Small
MN	Medium Negative
LN	Large Negative

Figure 2.5 Fuzzification sets

2.6.3.3 Inference Engine

The fuzzy logic inference engine assesses how closely the fuzzy input aligns with the predefined rules. Depending on the input conditions, it identifies which rules are applicable. The activated rules are then aggregated to produce the appropriate control actions. In the Kenyan context, the inference process is crucial for adapting boiler control systems to local operational conditions, such as variable fuel quality and fluctuating ambient temperatures, which are common challenges in many Kenyan industries. Jeremy K (2019), in his study on application of fuzzy in developing rules suggested that the inference engine relies on fuzzy operators like AND, OR, and NOT to evaluate the degree to which each rule applies, enabling nuanced decision-making that enhances system reliability and efficiency.

Recent studies in Kenya have demonstrated that optimizing the inference mechanism can significantly improve boiler performance and reduce emissions, especially when integrated with local sensor data and control systems (Malleesh B et al, 2023). Additionally, implementing tailored inference strategies that consider specific regional operational parameters such as fuel moisture content or local environmental conditions has proven effective in improving overall energy efficiency and sustainability in Kenyan industries. These advancements underscore the importance of context-specific

fuzzy inference systems in achieving optimal control and environmental compliance within Kenyan boiler operations

2.6.3.4 Defuzzification

After obtaining the fuzzy output, the next step is defuzzification, which converts fuzzy results into crisp values usable by the control system. The Centroid method is commonly used, wherein the center of the area under the aggregated fuzzy output curve is calculated. This provides a single actionable value for control implementation (Zhang et al.,2025).Defuzzification converts fuzzy sets into clear, actionable values. Several techniques are available for this process, and selecting the most appropriate method typically requires guidance from an expert system.

2.6.3.5 Membership Function

A membership function graphically represents the relationship between points in an input space and their corresponding membership values, which range from 0 to 1. It quantifies linguistic terms and visually depicts fuzzy sets. This function measures an element's degree of membership within a fuzzy set. Multiple membership functions can be utilized to fuzzify numerical values, but simpler functions are generally preferred as complex functions may not improve output accuracy. Membership functions are commonly classified as low, medium, or high.

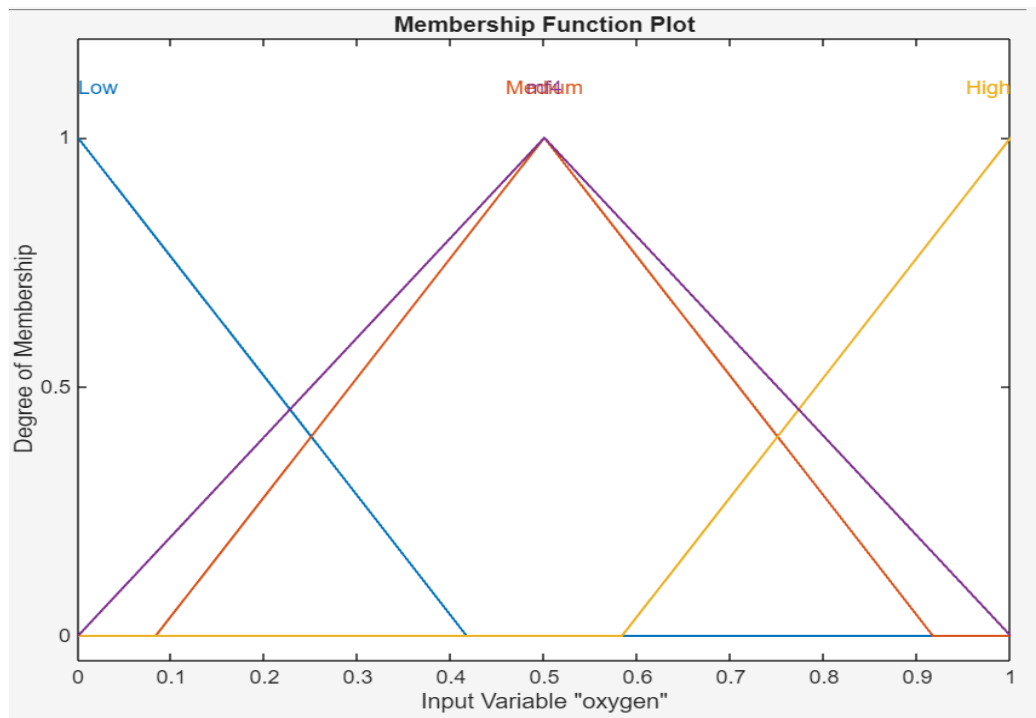


Figure 2.6 Triangular Membership function

The triangular membership function is one of the most prevalent shapes among various membership function designs. In this case, the input to the 3-level fuzzifier varies from 0 to 1.0, as determined by the researcher's convenience, thereby resulting in corresponding changes in the output.

2.6.3.6 Implementation and Testing

The implementation phase entails deploying the fuzzy logic control system in a real-world boiler setting. Extensive testing is necessary to evaluate performance, stability, and reliability. The system should undergo various operational scenarios to ensure it can handle fluctuations in fuel properties and energy demand. During testing, it is essential to monitor the system's response time, accuracy of control actions, and ability to maintain optimal efficiency under different load conditions (Zhang, C et al, 2025). In the industrial context, pilot implementations have shown that iterative testing and fine-tuning of the fuzzy control parameters are vital to accommodate local operational

variables such as inconsistent fuel quality and varying ambient temperatures, ultimately leading to more resilient and adaptive control systems.

2.6.3.7 Performance Evaluation

The implementation process also involves integrating the fuzzy logic control system with existing boiler management hardware and software. Compatibility challenges often arise due to legacy systems commonly used in many Kenyan industries; therefore, ensuring seamless integration is crucial for successful deployment. Custom interfaces and middleware solutions may be required to enable real-time data exchange between the fuzzy controller and the plant's control systems. Furthermore, training operators on system functionalities and troubleshooting procedures is essential to maximize system uptime and ensure safe operation during the testing and subsequent operational phases.

Post-deployment, continuous monitoring and data collection are vital to evaluate long-term system performance and identify areas for further optimization. In the Kenyan context, data-driven adjustments can help address seasonal variations, such as changes in ambient temperature and humidity, which influence boiler efficiency. Incorporating feedback from operators and real-time sensor data allows for adaptive tuning of the fuzzy rules is necessary for enhancing system robustness under varying operational conditions as stated by Liu Z et al (2020). This iterative approach ensures the control system remains effective, sustainable, and aligned with the specific needs of processing industries.

2.7 Critical literature review

The significance of optimizing boiler efficiency in wood-fired systems is underscored by the increasing focus on sustainable energy practices and the growing reliance on biomass as a renewable energy source in Kenya's tea factories. Numerous studies have

explored the relationship between fuel characteristics, combustion conditions, and overall boiler efficiency, revealing critical insights relevant to both industry and academia.

Veronica K. et al. (2024) published research in *Heliyon* detailing the optimization of biomass fuel mix for tea processing boilers in Kenya. The study, utilizing Response Surface Methodology (RSM), aimed to minimize costs while maximizing energy output. The research highlighted macadamia nutshells as a viable alternative or supplement to traditional fuelwood due to their superior energy density and lower moisture content, despite their higher cost.

Yang, X. et al (2019), discusses the role of biomass fuels in energy management plans. The author points out that using low-moisture wood can improve combustion efficiency, ultimately leading to better energy outcomes for processing plants. This aligns with the goal of minimizing waste and maximizing resource use in energy-intensive industries like tea processing.

Karambu G. (2020), in her research on environmental efficiency of small-scale tea processors in Kenya using the example of small-scale tea processors in the country, sought to understand the environmental efficiency of the small-scale agro-processors. Small-scale tea processors were chosen because they have been implementing environmental efficiency enhancing techniques in their production, yet no study had endeavored to test whether their initiatives were yielding positive results. The study adopted the innovative inverse data envelopment analysis approach on panel data to generate environmental efficiency scores, in the first step. In the second step, it analyzed the predictors of environmental efficiency using Tobit regression. Overall, the results showed that small-scale tea processors in Kenya were still environmentally inefficient,

recording a mean efficiency index of only 49%, despite previous initiatives to improve efficiency. Thus, the processors could reduce 51% of the environmentally detrimental inputs without compromising output.

Smith. et al. (2020) provide a comprehensive overview of biomass boiler technologies and their applications in various industries. Their research emphasizes the need for an energy management plan that incorporates advanced monitoring and control systems to optimize boiler performance.

Jones, (2019) examines the environmental benefits of using biofuels in industrial processes, including tea processing. The author argues that efficient energy management in woody biomass systems can significantly reduce greenhouse gas emissions, contributing to sustainability.

Martinez J. et al (2020) analyzed the economic feasibility of implementing biomass energy systems in developing countries. Their findings indicate that wood-fired boilers can provide a cost-effective solution to energy needs when paired with effective management strategies.

Maulin & Pardeed (2024) in their research on biomass energy for sustainable development examined how optimal biomass utilization can reduce forest management costs, help mitigate climate change, reduce risks to life and property, and help provide a secure, competitive energy source into the future. They alluded that the study provided a comprehensive review of biomass energy and focuses on in-depth understanding of various strategies to pretreat biomass including physical chemical, and biological. Explored multidisciplinary, novel approaches including AI for furthering the understanding and generation of models, theories, and processes in the field of

bioenergy and covered the sustainable development goals for bioenergy, including then related concepts of bioeconomy and the potential environmental impact from reliance on bioenergy.

Carvalho et. al. (2020) investigate the potential for improving energy efficiency in industrial boilers through various optimization strategies. Their insights are relevant to tea processing factories looking to improve their energy management practices.

In conclusion, optimizing boiler efficiency in wood-fired boilers involves a multifaceted approach that includes selecting appropriate fuel types, optimizing air-fuel levels, adopting advanced combustion technologies, and implementing effective operational practices. Continued research and innovation are essential in refining these systems to meet both efficiency and environmental sustainability goals in the context of renewable energy generation

2.7.1 The Direct Method

This method assesses boiler efficiency by comparing the energy absorbed by the working fluid to the total energy derived from the consumed fuel. Known as the "input-output method," it evaluates efficiency based on the total useful output against the heat input (Lahijani et al., 2018). The efficiency can be calculated using the following formula:

$$\begin{aligned} \text{Boiler efficiency, } \eta &= \frac{\text{Heat output}}{\text{Heat input}} \times 100 \\ &= \frac{Q \times H - h}{q \times \text{GCV}} \times 100 \dots \dots \text{Equation 1} \end{aligned}$$

Where Q =Quantity of steam generated per hour (kg/hr.)

H=Enthalpy of saturated steam (kcal/kg)

h =Enthalpy of feed water (kcal/kg)

q =quantity of fuel used per hour (kg/hr.)

GCV= Gross calorific value of fuel.

2.7.2 The Indirect Method

In this approach, the efficiency is derived from the total boiler losses subtracted from 100%.

This is where the efficiency is the difference of the boiler losses from 100% forms the boiler efficiency by indirect method.

Boiler efficiency by indirect method = $(100\% - L_1 + L_2 + L_3 \dots L_8)$Equation 2

Where:

L_1 to L_8 are the major losses in a steam boiler.

2.8 Steam Theory Fundamentals

The boiler system consists of a feed water system, steam system, and fuel system. The feed water system supplies water to the boiler and automatically regulates it to meet steam demands. Various valves allow for maintenance and repairs (Sabet, 2016). The steam system manages and directs steam produced by the boiler through pipes to points of usage, using valves to regulate pressure, which is monitored with steam pressure gauges. The fuel system encompasses all equipment needed to deliver fuel for heat generation, with the specific equipment dictated by the fuel type.

Feed water is the water supplied to the boiler for conversion into steam. This can originate from either condensate (returned steam) or treated raw water (makeup water) sourced externally from the boiler room and plant processes. To enhance boiler

efficiency, the feed water is often pre-heated by an economizer, which utilizes waste heat from flue gases (Sabet, 2016). Figure 2.8 illustrates a boiler system, labeling various losses associated with it, which can differ based on the boiler design and fuel type.

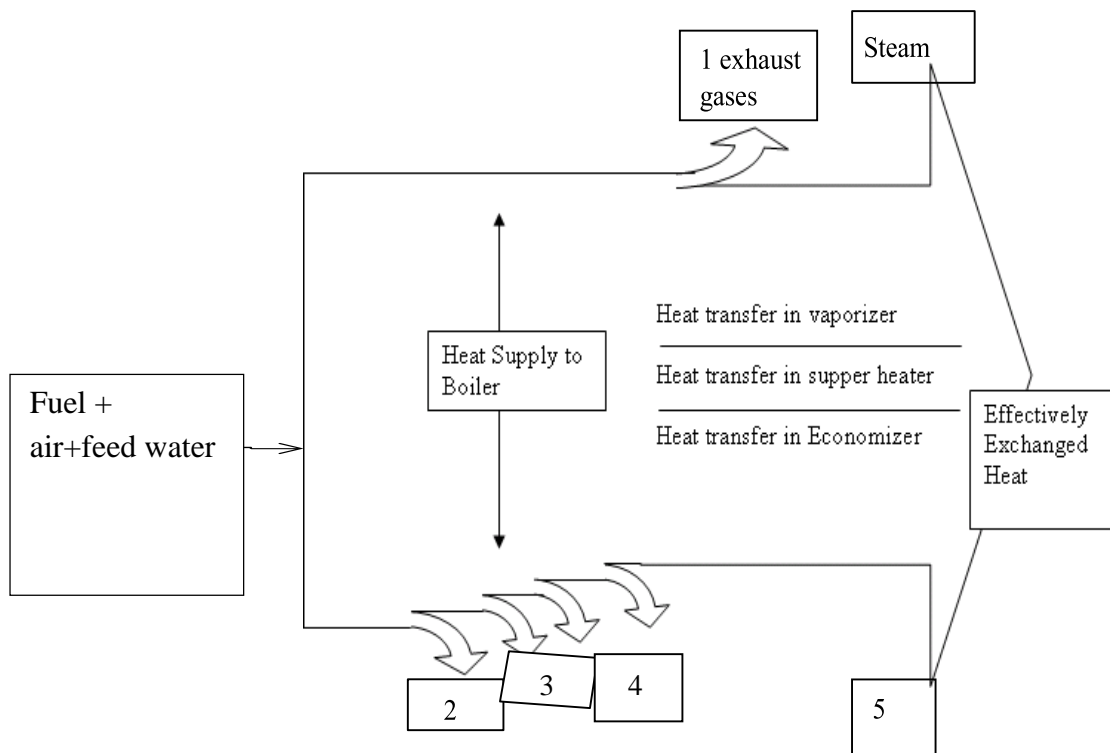


Figure 2.7 Sankey diagram of boiler losses

2.9 Energy Audit in tea factories

An energy audit is a systematic methodology designed to identify energy losses, quantify these losses, estimate potential savings, explore options for technological conservation, and evaluate the techno-economic implications of proposed interventions. This process aids industries in reducing energy consumption and encourages the adoption of energy-efficient technologies through training programs and workshops, facilitating the integration of sustainable and environmentally friendly technologies into the industrial sector in light of climate change (Senthil S 2023).

Energy conservation is essential for addressing the escalating challenges presented by the global energy crisis and its associated environmental impacts. Effective energy management is deemed critical for successful conservation efforts. This study focuses on the development of an “Energy Management System” and its implementation in practical settings. The program is structured as a continuous improvement cycle, beginning with the formation of an energy management team, followed by data collection, the generation of monitoring reports, and the execution of audits (Okeyo, 2020). Consequently, the performance of a process plant can be improved through the monitoring, analysis, and adjustment of key operational parameters, and, in some cases, modifications to the plant itself. This involves assessing energy distribution within the tea factories and identifying losses related to various energy applications. The scope and duration of the audit may vary according to the complexity of the tea factory and its specific operational needs and constraints.

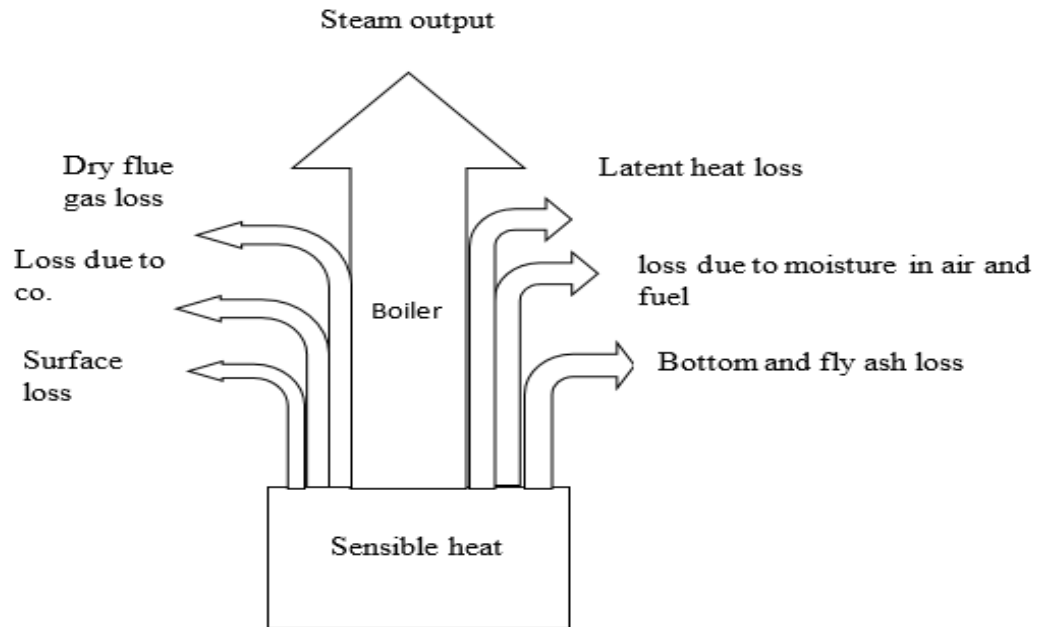


Figure 2.8 Common losses associated with the boiler

The researcher will adopt a systematic approach to the energy audit process, beginning with an analysis of the facilities historical and descriptive energy data. This initial phase will involve gathering specific information about the facility, including its layout and a comprehensive list of equipment that significantly impacts energy consumption. Prior to commencing the audit, the auditor must identify any specialized measurement tools required for the process. Additionally, a briefing on safety protocols is recommended as a precaution. Throughout the execution of the management program, two types of audits were performed at the plant: internal and external audits.

2.10 Chapter Summary

Chapter 2 offers the theoretical layout of multiple concepts of energy management practices (EMPs) in a boiler system, namely: cost management, prudent energy production, prudent consumption, prevention of energy loss, and optimization. The first two conceptions have a great connection as they strive to accomplish sturdy energy improvement. A literature overview related to EMP in boiler systems raises issues such as computational complexity, the need for expert knowledge in rule base development, and the difficulty of integrating fuzzy logic controllers with existing energy structures (Yang, X et al 2019). Arguably, the cross-cutting issue in this thesis is to optimize the boiler under study and develop an EMP to enhance efficiency in the system.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

Research methodology is defined as a systematic framework that guides a study in the selection and implementation of various methods aimed at achieving specific research objectives. In this study this chapter provides a comprehensive outline of the methodological approach utilized in the study. It strives to address key components including research design applied, study population, sample method, sample size, the research instruments employed, their validity and reliability. Additionally it covers the techniques for data collection and analysis, ethical considerations, as well as a final summary.

3.2 Research Paradigm

A research paradigm is a well-established model or framework for conducting research that has been endorsed by the academic community over time. Most research paradigms originate from one of two primary approaches: the positivist approach or the interpretivism approach. Each study aligned itself with one of these paradigms to shape the methodology and ensured that the research was conducted in a valid and appropriate manner. In addition to these two paradigms, various others have emerged, especially in the realm of social science research, as highlighted by Bryman (2021).

This study employs the "research onion" framework, which proposes that a research strategy can encompass action research, experimental research, interviews, surveys, case studies, or systematic literature review. Saunders, (2019) identifies series of considerations necessary for formulating a research methodology, emphasizing a journey from broad philosophical underpinnings to practical tactics as the researcher

moves inward through the layers of the onion. While Saunders's model is not without its limitations, it provides a framework that is very useful for consideration in a comprehensive methodology, thereby aiding in the understanding of design choices. The research onion effectively portrays the various stages involved in research project development and elaborates on the associated processes.

Utilizing the research onion helps in systematically designing a research methodology. Saunders et al. (2019) observed that employing the research onion requires progression from the outermost to the innermost layer. According to Saunders et al., the research process is akin to peeling back the layers of an onion, where the inner layers can only be examined once the outer layers have been removed. This methodology principle underscores the importance of adhering to the correct procedural steps to meet the study's objectives. The application of the research onion strategy was guided by the data needs and objectives of the study, which are aimed at formulating an Energy Management Plan (EMP) to reduce energy losses, lower greenhouse gas emissions, and alleviate environmental pollution.

3.3 Research Design

Research design in this research serves as the conceptual blueprint for conducting a study. Distinguished authors concur that research design involves developing a plan that steers the research process (Creswell & Creswell, 2018). This study on energy management plan for optimized wood fired boiler adopts a mixed-method approach. This combines both quantitative and qualitative techniques. This bolsters that no single research design exists in isolation, Bryman (2021), supports the incorporation of mixed methods in research claiming that this combination not only facilitates triangulation but also strengthens the validity, reliability, credibility, and dependability of the results.

Validity and reliability are linked to quantitative methodologies, while credibility and dependability relate to qualitative approaches.

The primary structure employed in this study is a cross sectional survey design within which the quantitative framework is domiciled. Qualitative techniques complement the quantitative approach in areas such as sampling technique, data collection procedure and data analysis. This qualitative perspective is in line with viewpoints from researchers like (Bryman, 2021) and (Creswell & Creswell, 2018), who characterize the qualitative approach as subjective and unstructured, which allows for a deeper understanding of the perspectives and practical experiences of research participants. While none of the five qualitative research designs fully aligned with the survey design, elements of the case study research was utilized to incorporate qualitative methods into sampling, data collection, and analysis on the other hand.

This enabled the researcher to gather comprehensive, systematic, and an in-depth information about specific areas of interest within their natural environments, as supported by (Orodho, 2015). This concept of mixed methods research traces back to 1959 when Campbell and Fiske pioneered the use of multiple methods to evaluate the validity of psychological constructs (Creswell & Creswell, 2018). The development highlighted introduced mixed methodologies that integrated qualitative methods such as focus group in wood fired boiler set up discussions and interviews with traditional quantitative surveys. Acknowledging the inherent limitations of each method, the mixed-methods approach allows for the biases of any one method to be balanced by the others employed. Moreover, this strategy permits researchers to utilize qualitative techniques to affirm findings derived from quantitative analyses.

This study employed a triangulation approach, as illustrated in Figure 3.1. Comprehensive analysis of the boiler data such as evaluation of moisture levels in wood fuel, monitoring the levels of emissions in the boiler under study, analyzing the air fuel requirements and development of an energy management plan was done guided by the fuzzy logic simulation results. Creswell & Creswell, 2018, alluded that within a triangulated mixed-methods framework, data collection and analysis take place in a unified phase of the research, with the greater weight attributed to each method determined by the specific research questions being explored.

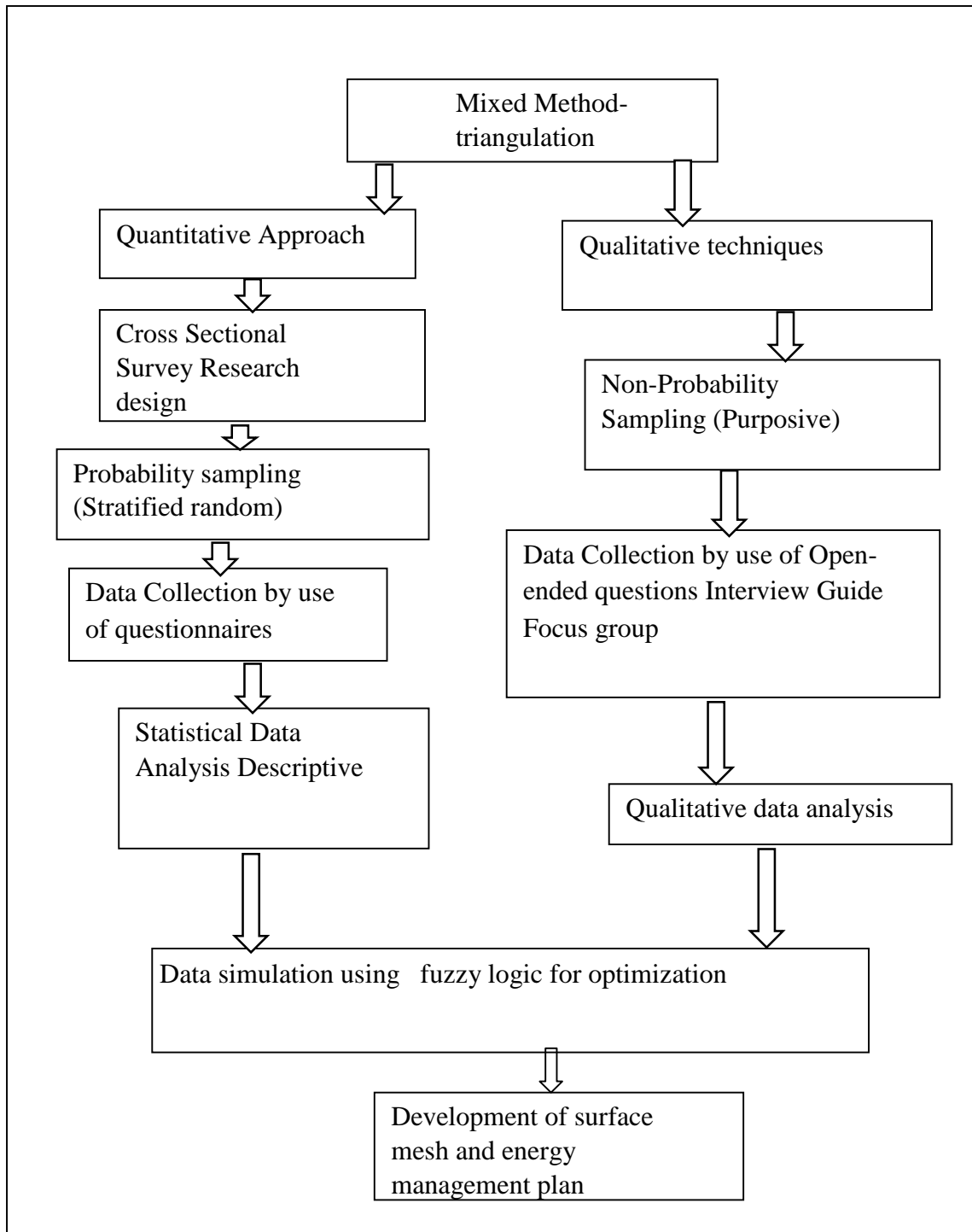


Figure 3.1: The systematic flow of the triangulation mixed method model flow diagram

Figure 3.1. Illustrates the systematic flow of the triangulation mixed method model flow diagram. On the left side of the flowchart, the quantitative strategy is depicted, highlighting the adoption of a cross-sectional survey research design. Data analysis employs statistical techniques such as descriptive statistics, paired sample t-tests, and

multiple regression. Conversely, the right side showcases qualitative methods utilized in sampling, data collection, and analysis. Both methodologies converge in the areas of data presentation, analysis and discussion, ultimately ensuring that the study's summary, conclusions, and recommendations are underpinned by both approaches.

3.4 Target Population

The target population encompasses the entire group of individuals from which a sample is drawn. It refers to the specific group that the study aims to investigate and draw conclusions about. In this research, the focus was on a tea processing factory in Kenya, chosen based on two key considerations that when a research is conducted within homogenous groups in a population then the process enhances the validity and reliability of findings. Secondly, the nature of the study, which revolves around energy planning and optimization, necessitated the selection of a factory that is a significant consumer of boiler energy as alluded by Alvi (2016). The tea factory under study has four boilers all wood fired. Two of these boilers are semi-automatic while the other two are manual. The tea processing facility under study provided invaluable data from the four boilers on firewood fuel usage, energy efficiency measurements, moisture content levels and flue gas analysis spanning a five-year timeframe from 2018 to 2023, which reflected the current operational state of the boiler.

3.5 Sampling Procedure and Sample Size

Sampling involves selecting a subset of cases to draw conclusions about the larger population. A sampling frame in this study served as the source material from which the sample was derived (Fricker, 2016). This study employed both probability and non-probability sampling designs. Probability sampling, which relies on random selection, allowed for estimating how findings from the sample may differ from the entire

population (Orodho, 2015). This method included stratified and cluster sampling techniques. In contrast, non-probability methods do not involve random selection, making it impossible to determine the likelihood of including each population element in the sample. Non-probability sampling techniques like purposive and snowball sampling were utilized to gather data from key informants in the boiler house.

3.5.1 Sampling Procedure

A multistage sampling approach was implemented, incorporating both purposive and snowball sampling methods. The initial stage involved two steps: evaluating the chosen factory based on its energy audit results, followed by determining the minimum number of steam energy processes across various categories. A non-proportional stratified random sampling method was then employed, ensuring that all population categories were represented in the sample to minimize estimation errors (Bryman, 2021). The subsequent stage involved creating lists to identify steam generation from wood fuel alongside energy conservation initiatives within the factory, allowing for comparisons regarding their efficacy and impact on data reliability and efficiency. (Kothari, 2004), recommends engaging multiple initial contacts in each stratum to enhance representation.

3.5.2 Sample Size

The population refers to a group of individuals or objects sharing observable characteristics, while a sample is a representative subset of that population. Determining the appropriate sample size depends on the study's objectives, population size, required precision, confidence level, and variability in the measured attributes. In this study, a sample of 72 assorted datasets was drawn from a total of 360 a ratio of 5:1 as alluded by Mumtaz A, et al (2020) to ensure fair representation . To enhance

representativeness and gather relevant insights, a formal questionnaire was distributed. For the focus group, five boiler technicians were specifically chosen for their expertise in boiler energy.

According to (Orodho, 2015), purposive sampling allows researchers to use their judgment to select respondents who accurately represent the population. Expert insights significantly augmented the information collected from the data. Given the abundance of available data, the sample size was statistically determined using Taro Yamane's formula introduced in 1967. Random sampling was applied to examine the potential effects of significant energy losses on the environment and various optimization opportunities. The formula for sample size calculation is:

$$n = \frac{N}{1+N(e)^2} \dots\dots\dots \text{Equation 3}$$

Where; n = sample size, N = target Population, and (e)²= probability error (derived from the confidence interval).

3.6 Data Collection Instruments

Numerous scholars have highlighted the effectiveness of questionnaires in gathering substantial information within a short time frame. The questionnaire was designed to ensure reliability regarding the variables specified in the conceptual framework. Additionally, an interview schedule and focus group discussion guide were employed to guarantee that comprehensive data were obtained. Neeraj K, (2022) advocated that for using multiple instruments to promote triangulation, thereby enhancing the study's validity and reliability. Each instrument began with consent forms and concluded with

remarks to uphold ethical considerations, with all research tools developed by the researcher.

3.7 Interview Guide

An interview guide consisted of a standardized set of questions posed by the interviewer, ensuring consistency across interviews. This guided both structured and open-ended questions to capture detailed and thorough data. The interview guide specifically aimed to explore the impact of optimization on boiler energy. It provided a platform for researcher to prompt respondents, allowing for nuanced data collection related to wood fuel suitability, greenhouse gas emissions, energy losses, and boiler efficiency. Each interview session lasted approximately 20 minutes to create balance to participant attention span.

3.8 Group Discussion Guide

The focus group discussion guide has gained popularity as a qualitative data collection tool. This research utilized a guide which comprised of four sections that comprehensive responded to four research objectives as shown in table below.

Table 3.1 Key section for group discussion guide

Section	Topic	Description
A	Energy Usage and Energy Audits	Explores current energy consumption patterns, operational practices, and insights from energy audits. Participants share experiences related to fuel consumption, efficiency measures, and areas needing improvement to identify energy losses.
B	Types of Energy Losses in a Wood-Fired Boiler	Focuses on identifying specific energy losses such as incomplete combustion, heat escape through flue gases, moisture content in wood, and heat transfer inefficiencies. This helps in pinpointing where improvements can be made.
C	Evaluating Boiler Efficiency	Gathers perceptions on boiler performance, methods used for efficiency measurement, challenges faced, and potential technological or procedural enhancements to optimize efficiency.
D	Moisture Levels and Air-Fuel Ratio	Examines the impact of wood moisture content and the importance of maintaining the correct air-fuel ratio for optimal combustion, reduced emissions, and better energy utilization.

3.9 Pilot Testing

Pilot testing is a preliminary study aimed at assessing logistics and gathering preliminary data prior to a larger investigation. In his study on instruments used in the collection of data in research, Neeraj K, (2022) stated that pilot studies serve to test questionnaire effectiveness with a smaller sample size relative to the planned total. In this research, pilot testing aimed to identify potential design and procedural deficiencies. During this phase, both the interview guide and focus group protocols were developed and refined based on feedback from boiler operators and engineers. The pre-test sample was small, typically comprising about 1% to 10% of the intended

total sample size (Kothari & Garg, 2014), with 24 respondents participating, representing 10% of the planned 240 boiler operators participants.

3.10 Pre-testing of Instruments

The pre-testing of both the quantitative and qualitative data collection tools was conducted to ensure their validity and reliability prior to the main data collection phase. Validity pertains to the instrument's capacity to accurately measure the constructs it is intended to assess, which is essential for generating meaningful and credible results. For a tool to be considered valid, its content must be directly relevant to the research objectives and address the identified research gap (Creswell & Creswell, 2022). The pre-testing process aims to enhance the precision and relevance of the findings by identifying and controlling potential confounding variables, thus increasing the overall confidence in the study's outcomes. Reliability, on the other hand, refers to the consistency and stability of the results obtained from the instrument over time or across different contexts. Ensuring reliability involves assessing whether the tool yields consistent results upon repeated application, which is vital for establishing the trustworthiness of the data collected (Bryman, 2018; Johnson et al., 2022). Together, validation and reliability testing serve to refine the instruments, ensuring they are both accurate and dependable for capturing the necessary data.

3.11 Validity of Data Collection Instrument

The researcher undertook a validation process for the data collection instruments. This involved comprehensive review by experts in the field, specifically boiler engineers. Validation guidelines were followed to ensure thorough evaluation. The instruments were designed to incorporate parameters necessary for testing and data acquisition. Designing a fuzzy rule base necessitates an interactive approach, where knowledge collection is regarded as a critical and often complex task. One significant advantage of

employing fuzzy logic is its capacity for validation through expert input, particularly from boiler operators and engineers, before deploying the rule base in practical applications. This validation process ensures that the rules accurately reflect operational realities and expert insights, thereby enhancing the reliability and effectiveness of the system.

The procedure for fuzzy logic optimization, as depicted in Figure 3.2, begins with a three-step data collection process. The first step involves identifying relevant variables, which serve as the linguistic variables forming the foundation of the rule base. Next, the specification of qualitative metrics is essential; this step involves defining the degrees of truth and falsehood for each variable, thereby creating linguistic terms that facilitate interpretability within the fuzzy system. The final step encompasses the formulation of concepts and their manipulations, where cases to be considered are detailed, along with their characteristics and the appropriate actions to be taken under various conditions. This structured approach ensures that the fuzzy rule base is both comprehensive and aligned with expert knowledge, ultimately leading to more accurate and robust fuzzy inference systems.

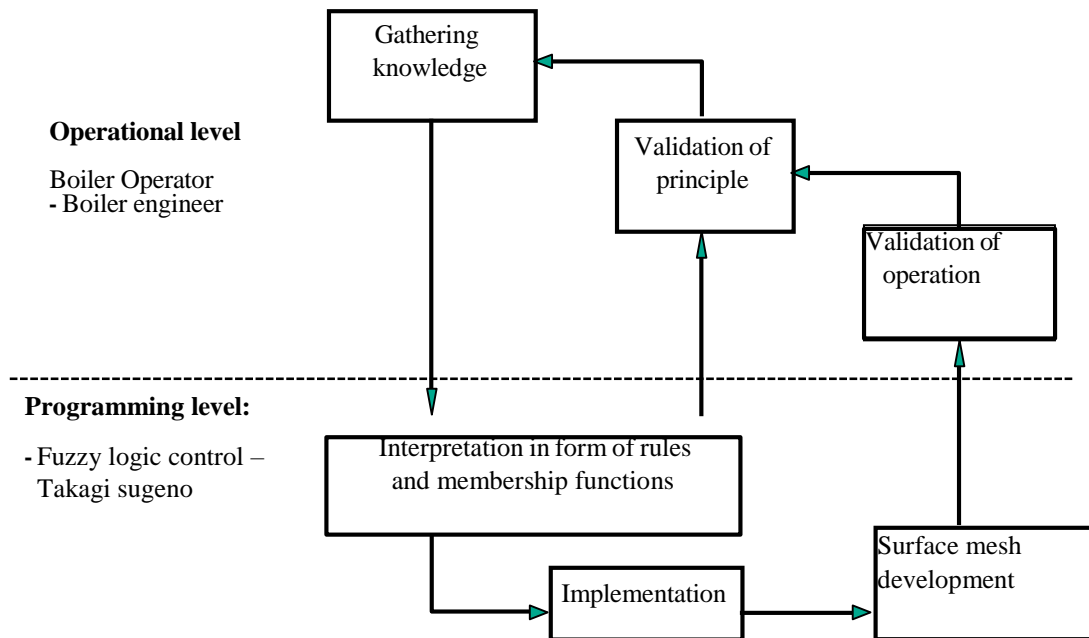


Figure 3:2: Fuzzy logic optimization flow

Transcribing into fuzzy rule form is a relatively simple process. However, to enhance readability of the rule base, efforts were made to create as few membership functions and rules as possible, which also helps limit the number of parameters that need to be fine-tuned. It is noted that adding rules to accommodate new situations is generally easier than removing existing ones. The next step involves validating the knowledge, which occurs through several stages: presenting the rule base to experts who contributed to knowledge acquisition and facilitating discussions. The purpose of these discussions is to pinpoint any unaddressed points and ensure the clarity of the rules. Finally, simulations were conducted, allowing the researcher to compare the behavior of the rule base with the expected outcomes of pre-selected cases.

Table 3.2 Data collection tool**Initial Data (Before Optimization):**

Parameter	Boiler Level I	Boiler Level II	Boiler Level III	Boiler Level IV	Sum
Burner/Mill Activity	Not active	All active	E2, E3	All active	E1, E4
Firewood consumption (kg/s)	0.5	1.2	0.8	0.5	2.5
Core air (kg/s)	10	22	15	10	47
Primary air (kg/s)	8	18	12	8	38
Secondary air (kg/s)	9	20	14	9	43
Tertiary air (kg/s)	3	5	4	3	12
OFA II (kg/s)	2	4	3	2.02	9
OFA III (kg/s)	1	2	2	0.95	5
Protective air (kg/s)	1.5	3	2.5	1.5	7
Bottom air (kg/s)	5	11	7	5	23
Total air (kg/s)	40.5	85	49.5	40.5	175
Total air excess	15%	20%	18%	15%	-
Primary/Secondary air (K)	450	460	455	450.1	-

After Optimization:

Parameter	Boiler Level I	Boiler Level II	Boiler Level III	Boiler Level IV	Sum
Coal (kg/s)	0.45	1.1	0.75	1.2	2.3
Core air (kg/s)	9.5	20	14	20	43.5
Primary air (kg/s)	7.5	17	11.5	17.1	36.0
Secondary air (kg/s)	8.5	19	13	19	40.5
Tertiary air (kg/s)	2.8	4.5	3.8	4.5	11.1
OFA II (kg/s)	1.8	3.5	2.8	3.51	8.1
OFA III (kg/s)	0.9	1.8	1.8	1.8	4.5
Protective air (kg/s)	1.2	2.5	2	2.5	5.7
Bottom air (kg/s)	4.5	9.5	5	9.6	20
Total air (kg/s)	36.7	83.3	50.6	83.1	170.4
Total air excess	12%	15%	13%	15%	-
Primary/Secondary air (K)	440	455	452	453	-

(Source :Audit data from factory under study)

The study commenced identification of inefficiencies in the wood fired boiler energy consumption. In this process particular issues such as excess air, incomplete combustion, and suboptimal fuel-air ratios were considered. This was done through reviewing existing literature, industrial standards, and analyzing data that had already been accurately collected from the wood fired boilers through established measurement systems in the factory under study. As shown in Table 3.2 above, these measurements included key parameters such as wood fuel consumption, air flow rates, boiler temperatures, and excess air levels, which were obtained using sensors, flow meters, and control systems that were previously calibrated and in operation. This existing dataset provided a reliable baseline of the current performance of the four wood-fired boilers, allowing for a thorough understanding of their operational efficiency without conducting any new experiments.

The collected data was then subjected to detailed analysis using statistical and computational tools such as ANOVA, MATLAB, fuzzy logic control, and Response Surface mesh (RSM). These techniques facilitated the exploration of the relationships between operational parameters and boiler performance over defined time, enabling the identification of key factors influencing efficiency and emissions. The fuzzy logic models, in particular, helped develop comprehensive surface mesh that captured the complex nonlinear interactions among variables such as fuel, water and air as key inputs and efficiency and gas emission as outputs.

Based on this analysis, operational recommendations were formulated to optimize boiler performance. These included adjustments to fuel and air inputs, combustion temperatures, and other critical parameters, all derived from the insights gained through the data analysis. The effectiveness of these recommendations was validated by examining the improvements in fuel consumption, excess air levels, and combustion

efficiency revealed by the statistical evaluation. To ensure sustained energy savings and ongoing performance improvement, real-time monitoring systems were implemented, providing continuous assessment of boiler operation and facilitating further optimization and maintenance. This approach eliminated the need for new experimental testing, relying instead on the rigorous analysis of existing, accurately measured operational data to guide on development of energy management plan.

3.12 Reliability of Data Collection Instrument

The reliability of the data collection instruments was assessed using statistical analysis. The correlation coefficient, often referred to as the reliability coefficient, is one of the most widely used methods for estimating reliability (Kothari, 2004). Common techniques for gauging test reliability in educational research include test-retest reliability, parallel forms, split-halves, and internal consistency measures. This study examined all standard methods of reliability estimation but opted solely for Cronbach's alpha as a measure of internal consistency. Internal consistency evaluates how consistently a set of items measures a particular behavior or trait within a test. For internal consistency to exist, reliability estimates are based on the average inter-item correlations within the test. Orodho (2015) notes that Coefficient alpha is the most frequently employed method for assessing internal consistency in the behavioral sciences. First recognized for its wide applicability by Cronbach in 2004, it is often referred to as Cronbach's alpha. Internal consistency coefficients tend to increase with the number of items, up to a certain threshold. For example, a test with five items may correlate at 0.40 with true scores, while a twelve-item test may correlate at 0.80 (DeVellis, R. 2016). As a result, individual items are expected to show only minimal correlations with the true scores. If the coefficient alpha is very low, it may indicate that the test is insufficiently lengthy or that the items are not closely related. Coefficient

alpha is particularly effective for estimating reliability for item-specific variance in unidimensional tests. Since Cronbach's alpha assesses internal consistency, which gauges the degree of interrelatedness among items, it is generally recommended for evaluating the reliability of scales when multiple summated scales are employed, as is the case in this study (Cortina, 1993).

The formula for Cronbach alpha is:

$$\alpha = \frac{K\bar{r}}{(1 + (K - 1)\bar{r})}$$

Where

K = Number of indicators or number of c

\bar{r} = Mean inter-indicator correlation

Cronbach's alpha is widely regarded as the primary method for estimating the reliability of an instrument (Bryman, 2012). When all the questions for both dependent and independent variables are analyzed for reliability, a Cronbach Alpha level is achieved. George and Mallery (2019), posit that Cronbach's Alpha values of 0.9 and above indicate excellent reliability, while values between 0.8 and 0.9 are considered good as summarized in the table below.

Table 3.3. Cronbach's alpha ranking

Cronbach level	Rank
$\alpha \geq 0.9$	Excellent
$0.8 \leq \alpha < 0.9$	Good
$0.7 \leq \alpha < 0.8$:	Acceptable
$0.6 \leq \alpha < 0.7$	Questionable
$0.5 \leq \alpha < 0.6$	Poor
$\alpha < 0.5$	Unacceptable

In examining the advantages and drawbacks of different reliability tests, this study opted for the Cronbach's alpha method, setting a threshold of 0.7 as acceptable. The Statistical excel software was utilized for calculating the alpha. Bryman (2012) notes that the software offers a function to compute the alpha value while excluding specific items; if the alpha value substantially increases upon deleting any item that becomes a candidate for exclusion from the scale. Furthermore, reliability can be enhanced by clearly wording items, simplifying test instructions, and effectively training raters by clearly outlining the scoring rules.

3.13 Data Processing and Analysis

Data analysis involves systematically arranging information into meaningful patterns. The collected data was reviewed and treated for completeness and consistency. Mumtaz A et al (2020), recommends analytical methods for data analysis which aligns with the characteristics of the research design and the nature of the data collected over time. The application of this selected analysis encompassed both quantitative and qualitative data evaluation techniques. For each research question, the relevant data analysis is described, relevant data summaries presented, and interpretations made before addressing the subsequent research question. In this study, the methodology of Define Measure Analyse Interpret and Control (DMAIC) alongside application of the Kanban technique was applied.

Table 3.4 Data processing and analysis

S/N	Specific Objective	Independent Variables	Dependent Variables	Data Source	Method of Analysis
1	To investigate the effect of moisture content of wood fuel on the efficiency and operational performance of the wood-fired boiler system in the tea factory.	- Moisture content of wood fuel (%). -Type and size of wood fuel.	- Boiler efficiency (%). - Steam output and fuel consumption. - Combustion stability.	Laboratory analysis of wood samples, boiler operation logs, questionnaires.	Quantitative (correlation); qualitative observations.
2	To evaluate the relationship between air-fuel ratio and overall efficiency in the wood-fired boiler system.	- Air-fuel ratio (measured via flue gas analyzers).	- Overall boiler efficiency (%). - Combustion completeness indicators (CO, CO ₂ levels).	Flue gas analysis reports, operational data logs.	Quantitative analysis (correlation, regression); possibly fuzzy logic modeling.
3	To assess the environmental implications of flue gas emissions produced by the boiler and identify potential mitigation strategies.	- Emission levels of SO ₂ , NO _x , CO, particulate matter.	- Environmental impact indicators. - Compliance with emission standards.	Flue gas sampling and laboratory analysis data.	Quantitative analysis (emission profiling), qualitative assessment of mitigation strategies.
4	To analyze surface heat losses within the boiler system and determine their effect on overall energy efficiency.	- Surface temperatures of boiler components.	- Surface heat loss (energy loss in kW or percentage). - Overall energy efficiency.	Temperature sensors, thermal imaging, boiler operational data.	Quantitative analysis (heat transfer calculations, efficiency assessment)

3.13.1 Factor analysis

In this study factor analysis was conducted to identify key items, retaining the most essential ones considered for data analysis. Exploratory Factor Analysis (EFA) was

employed to decrease the number of variables (questions) since a high number of items can complicate the study. Moreover, some variables may represent different aspects of the same underlying construct. This method clusters similar variables to form a smaller number of factors that can effectively account for the variance observed in the larger set of variables. The resulting factors were then utilized for further analysis. Initially, the appropriateness of factor analysis concerning sample size was evaluated. According to contemporary guidelines in factor analysis, the categorization of sample sizes includes: 100 is considered poor, 200 is fair, 300 is good, 500 is very good, and 1000 or more is excellent. With a sample size of 240, this study is deemed suitable for applying the Kaiser-Meyer-Olkin (KMO) and Bartlett's Test to determine the factors to retain, using the principal components analysis (PCA) method. This analysis encompasses all variance, including that arising from correlation coefficients and error variance (Priyabrata P 2021). The KMO value, which evaluates sampling adequacy, should exceed 0.5 for satisfactory factor analysis to occur. Additionally, the Kaiser criterion was applied to retain factors with Eigen values greater than 1.

3.13.2 Hypothesis Testing

Hypothesis testing is a systematic and formal procedure used to assess the validity of a claim regarding a population based on sample data. In this research the method employs sample evidence and probability theory to determine whether the hypothesis is reasonable to be accepted or unreasonable for rejection.

Table 3.5 Details of hypothesis testing

Hypothesis	Test Statistic	Accept/ Reject Criteria
H_1 moisture content does not have a significant effect on overall boiler system performance	Anova test Two factors without replication	Accept H_0 if $p \geq 0.05$ or reject if $p \leq 0.05$ Positive linear relationship if correlation coefficient = +1, negative linear relationship = -1 and no linear relationship = 0 Cronbach alpha determination
H_2 Air-fuel does not have a significant effect on overall fuel consumption	Anova test Two factors without replication	Accept H_0 if $p \geq 0.05$ or reject if $p \leq 0.05$ Positive linear relationship if correlation coefficient = +1, negative linear relationship = -1 and no linear relationship = 0 Cronbach alpha determination
H_3 surface heat loss does not have a significant on overall boiler performance	Anova test Two factors without replication	Accept H_0 if $p \geq 0.05$ or reject if $p \leq 0.05$ Positive linear relationship if correlation coefficient = +1, negative linear relationship = -1 and no linear relationship = 0 Cronbach alpha determination
H_4 flue gases do not have a significant effect on boiler efficiency	Anova test Two factors without replication	Accept H_0 if $p \geq 0.05$ or reject if $p \leq 0.05$ Positive linear relationship if correlation coefficient = +1, negative linear relationship = -1 and no linear relationship = 0 Cronbach alpha determination

3.14 Fuzzy logic techniques

In this study, fuzzy logic was employed as a decision-making tool to optimize the operational parameters of the wood-fired boiler. The methodology involved developing a fuzzy inference system that could interpret uncertain and imprecise data collected

from the boiler's operational environment. Key input variables, such as moisture content, air-fuel ratio, and combustion temperature, were first fuzzified into predefined fuzzy sets using membership functions. A rule base was then constructed based on expert knowledge and empirical observations, linking these input variables to output variables related to boiler efficiency and emissions. Jeremy K (2019), alluded that fuzzy inference system if properly implemented can process real-time input data through the rules to generate fuzzy output sets, which are subsequently defuzzified into actionable control signals. In this context signals in this study were used to automatically adjust operational parameters, such as airflow rate and fuel feed rate, aiming to improve overall energy efficiency and reduce emissions. The system's performance was validated through comparison with traditional control methods, demonstrating its effectiveness in managing the inherent uncertainties of biomass combustion processes.

3.15 Ethical Consideration

This study strictly adhered to established ethical standards in research to ensure the integrity and credibility of the findings, as well as the protection of participants' rights and well-being. The research measures were implemented.

3.15.1 Informed Consent

Prior to initiating data collection, all participants involved in the study including factory staff, technicians, and relevant management personnel were provided with detailed information regarding the objectives and scope of the research. This included explanations of how their input and operational data would contribute to optimizing boiler performance, potential implications for factory operations, and the benefits of improved efficiency and reduced emissions. Participants were informed about their

right to decline participation or withdraw at any stage of the study without facing any repercussions or penalties. To ensure voluntary participation, written informed consent was obtained from each individual after clarifying any questions and confirming their understanding of the study's purpose and procedures. This process not only adhered to ethical standards but also fostered trust and transparency between the researchers and participants, which is essential in industrial research settings.

3.15.2 Anonymity and Confidentiality

Given the sensitive nature of operational data and proprietary factory information, strict measures were implemented to uphold participant anonymity and data confidentiality. All collected data were anonymized by removing or coding personal identifiers such as names, employee IDs, or specific operational details that could directly link to individual personnel or specific factory sections. These identifiers were stored securely in encrypted digital files, separate from the main dataset. Access to raw data was restricted solely to authorized research personnel who signed confidentiality agreements. During analysis and reporting, data were presented in aggregated or anonymized forms to prevent identification of individuals or specific factory units. Maintaining confidentiality was crucial not only for ethical compliance but also for preserving the trust of the factory management and staff, thereby ensuring ongoing cooperation and data integrity.

3.15.3 Ethical Approval

This research proposal was submitted for review and approval to the National Council for Science and Technology and Innovation (NACOSTI) of Kenya, ensuring adherence to national ethical guidelines governing research involving industrial and human participants. The approval process involved a comprehensive review of the research

methodology, data management plans, consent procedures, and potential risks and benefits. The approval certificate was obtained prior to any field activities, confirming that the study met ethical standards related to participant safety, data integrity, and responsible conduct of research. Compliance with both national and international ethical standards reinforced the credibility and integrity of the research process, which is particularly important given the involvement of industrial stakeholders and sensitive operational data.

3.15.4 Conflict of Interest Disclosure

All potential conflicts of interest were transparently disclosed at the outset of the research. This included any financial interests, affiliations, or relationships that could influence the objectivity of the study, such as consultancy roles with boiler manufacturing companies or funding sources from industrial partners. Any identified conflicts were managed according to established legal and institutional policies, including recusal from certain decision-making processes or independent review of data analysis. This transparency was essential to ensure the integrity, impartiality, and credibility of the research findings. Furthermore, the study maintained an open dialogue with all stakeholders to prevent bias and promote ethical research practices aligned with academic standards and industrial confidentiality requirements.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1. Introduction

This chapter deals with an analysis of the results. The data was collected from a wood-fired boiler. Data was organized and treated for analysis. Analysis was done using Matlab fuzzy logic software and Excel software to verify each of the hypotheses proposed. Some of the tests used to measure the hypothesis were the reliability test using Cronbach alpha, ANOVA, and FUZZY logic optimality test which enabled the development of an energy plan to mitigate the challenges in the boiler under study.

4.1.1 Data validation

The periodogram is a tool that helps analyze signals in the frequency domain by estimating their Power Spectral Density (PSD). It provides insights into the dominant frequencies present in a signal and their power levels. When applied to the validation of real versus theoretical data, it helps evaluate how closely the data aligned with the theoretical model in terms of frequency content. Frequency Deviation defines the absolute difference between the dominant frequencies of the two signals. A spectral density for the boiler under consideration yielded as shown below.

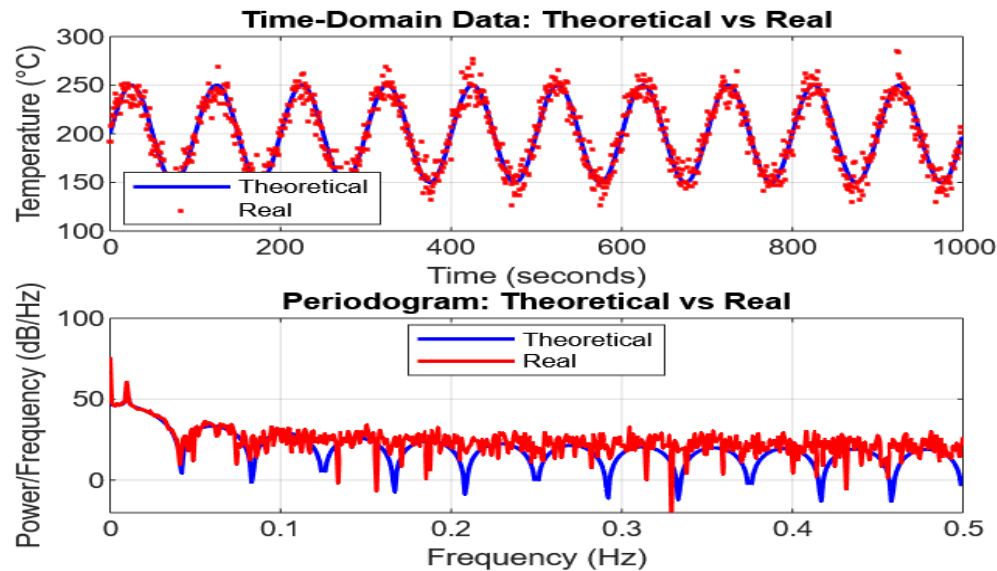


Figure 4.1 Comparison of theoretical and real data in time and frequency domains

The time domain analysis examined the data directly as a function of time. It focused on characteristics specifically trends within the data's sequence. In a signal displayed a representation in a physical process, time domain analysis revealed the rate of change with a presence of oscillations, The periodogram, on the other hand, is a frequency domain analysis technique. It estimated the power (or variance) of different frequencies present in the data. By transforming the data from the time domain to the frequency domain, the periodogram identified the frequencies at which the signal has the most energy. This allowed for the detection of periodicities and cyclical patterns that might be hidden in the time-domain representation. It's crucial that the periodogram provided a direct measure of the power at each frequency, which was helpful for understanding the relative importance of different frequencies in the data. The results of time domain and periodogram analysis were found close in the sense of identical values. In figure 4.1 above both time/temperature and frequency/power domain frequencies are very

close, an indication that the real data closely follows the periodic nature of the theoretical model and thus validating the data.

4.2 Pilot Study

A pilot study was conducted to evaluate the reliability of the questionnaires using a sample of 20 respondents. The reliability assessment involved ANOVA analysis conducted with Excel software, and Cronbach's Alpha was computed to gauge the internal consistency of the instrument used for data collection. The findings are illustrated in Table 4.1.

Table 4.1 : Two-factor ANOVA and Cronbach Alpha

Source of Variation	SS	Df	MS	F
Rows	70.54	4	17.635	9.163544
Columns	11.79	19	0.620526	0.322439
Error	146.26	76	1.924474	
Total	228.59	99		
Cronbach's Alpha =0.891				

A Cronbach's Alpha of 0.891 is considered to demonstrate good reliability according to standard benchmarks: When all the questions for both dependent and independent variables were analyzed for reliability, a Cronbach Alpha of 0.891 was achieved. George and Mallery (2019), posit that Cronbach's Alpha values of 0.9 and above indicate excellent reliability, while values between 0.8 and 0.89 are considered good as summarized in the table below.

Table 4.2. Cronbach's alpha ranking

Cronbach level	Rank
$\alpha \geq 0.9$	Excellent
$0.8 \leq \alpha < 0.9$	Good
$0.7 \leq \alpha < 0.8$:	Acceptable
$0.6 \leq \alpha < 0.7$	Questionable
$0.5 \leq \alpha < 0.6$	Poor
$\alpha < 0.5$	Unacceptable

Achieving a Cronbach's Alpha of 0.891 in this study confirms that the questions used to assess various aspects of wood-fired boiler performance are dependable. This reliability ensures that subsequent analyses, such as identifying key factors influencing boiler efficiency or emission levels, are based on stable and consistent data, thereby strengthening the validity of the research outcomes.

4.2.1 Independent Variable: Effect of moisture content to the efficiency of the boiler.

Table 4. 3 Moisture content on wood fuel vs thermal efficiency when 1TPH of steam is produced

S/No	Moisture content in wood per kg (%)	Consumption of wood to produce 1 TPH of steam	Thermal efficiency
1.	10	73.38	0.865
2.	20	87.49	0.878
3.	30	107.65	0.871
4.	40	129.06	0.864
5.	50	169.27	0.845
6.	60	245.03	0.819

Based on the findings, it has been noted that to generate 1 TPH of heat in the boiler furnace, 73.5 kg of wood with a moisture content of $W = 10\%$ is burned. When wet wood with a moisture content of $W = 60\%$ is combusted, the lower heat value results in a significant decrease in energy efficiency to 6.4%, requiring 3.3 times more fuel to produce the same amount of heat. Consequently, there is an improvement in thermal efficiency compared to the combustion of dried wood, as illustrated in Fig.4.2

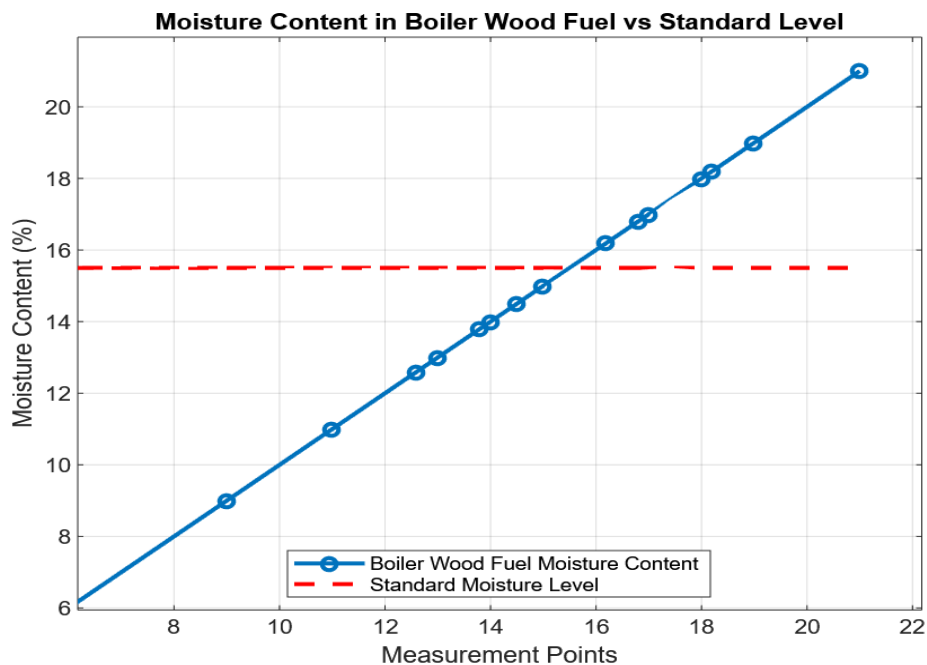


Figure 4.2: Moisture measurement in wood fuel

The diagram in figure 4.2 illustrates the process of monitoring and managing moisture content in boiler wood fuel through an iterative measurement approach. The blue line with circles represents the actual measured moisture content values at various measurement points, showing how moisture levels change across different samples or over time. The red dashed line indicates the standard or ideal moisture level, approximately 15.8%, which the boiler wood fuel should ideally have to ensure efficient combustion and optimal fuel performance. The measurement points marked along the graph correspond to specific instances where moisture content was recorded.

The trend line fitted through the measured data points demonstrates the overall pattern or trend of moisture content as the measurements progress, revealing whether the moisture is increasing, decreasing, or remaining stable over time.

Initially, the moisture content begins at around 6% at the first measurement point, which is well below the standard level. As measurements continue, the moisture content gradually increases, eventually surpassing 20% at the last point. This variation underscores the importance of the iterative process, which aims to adjust operational conditions such as drying processes or moisture control during storage to keep the moisture content as close as possible to the target level. Comparing the measured values to the standard moisture level helps identify deviations that may require corrective actions. When moisture content exceeds the recommended level, it indicates potential issues like excess moisture in the fuel, which can affect combustion efficiency and may necessitate process adjustments such as additional drying or improved storage practices. Overall, this iterative measurement and comparison process is crucial for maintaining optimal moisture levels in boiler wood fuel, thereby enhancing energy efficiency and ensuring consistent fuel quality.

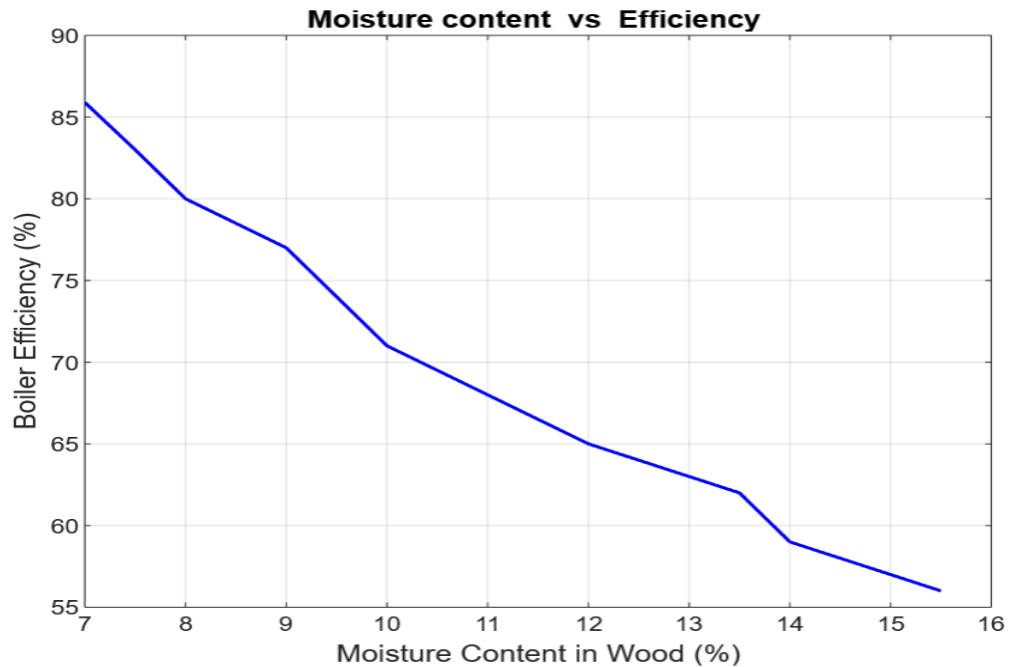


Figure 4.3: Correlation between fuel wood moisture content and the boiler efficiency

The graph in figure 4.3 illustrates the inverse relationship between moisture content in wood and boiler efficiency, demonstrating that as moisture content increases from approximately 7% to 15%, boiler efficiency consistently decreases from around 85% to about 55%. This trend emphasizes the importance of controlling moisture levels in wood fuel, as higher moisture content leads to lower combustion efficiency, likely due to increased energy required to evaporate the excess water, which reduces the overall energy available for heat generation. The data points suggest that maintaining moisture content closer to the lower end of this range can significantly enhance boiler performance, underscoring the need for effective drying or moisture management strategies. This relationship highlights the critical balance needed in fuel preparation processes to optimize efficiency and ensure sustainable operation.

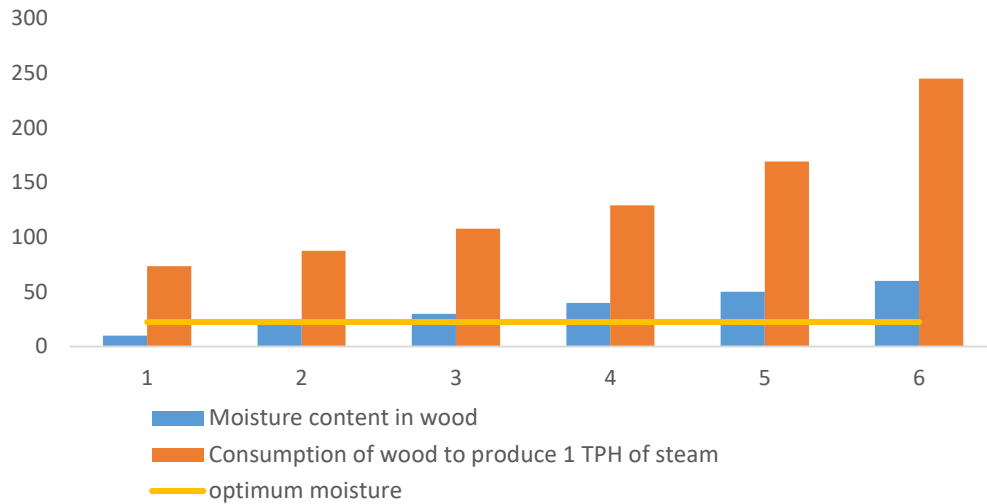


Figure 4.4: Correlation Between moisture content and firewood fuel consumption

When the optimum moisture content of 22.3 % is exceeded the wood consumption rate drastically increases because more of the energy is first lost in drying the moisture in firewood before it burns.

4.2.2 Independent Variable 2 - The Impact of Air-fuel on Fuel Combustion

The moisture content of wood chips plays a significant role in influencing their combustion behavior and, consequently, the overall efficiency of the boiler. An evaluation was carried out to analyze how variations in the air-fuel ratio impact the combustion process and thermal efficiency. The assessment assumed that the wood chips have an average composition with moisture content ranging from 10% to 60%. To ensure accurate analysis, the air-fuel ratios corresponding to complete combustion conditions were recorded and documented.

Table 4.4: Input values for calculation

Carbon (C)	Hydrogen (H)	Nitrogen(N)	Oxygen(O)	Ash(A)	Moisture content(W)
0.441	0.055	0.002	0.39	0.012	0.1
0.392	0.049	0.002	0.347	0.01	0.2
0.343	0.043	0.001	0.304	0.09	0.3
0.294	0.037	0.001	0.26	0.08	0.4
0.245	0.031	0.001	0.216	0.07	0.5
0.215	0.027	0.001	0.185	0.06	0.6

In addition, it was assumed that incomplete combustion occurs under certain conditions, resulting in elevated carbon monoxide (CO) levels in the exhaust gases that may approach emission limits. Standard data for oxygen (O₂) and carbon dioxide (CO₂) concentrations were used based on typical wood chip combustion scenarios. The input values in Table 1 were utilized to determine the corresponding air-fuel ratios. It was also observed that both complete and incomplete combustion conditions and thus the efficiency are influenced by the moisture content of the wood chips. Higher moisture levels tend to decrease combustion efficiency by requiring more air for vaporization and combustion, which affects the optimal air-fuel ratio. Therefore, understanding and controlling the air-fuel ratio in relation to moisture content is essential for optimizing boiler efficiency and minimizing emissions.

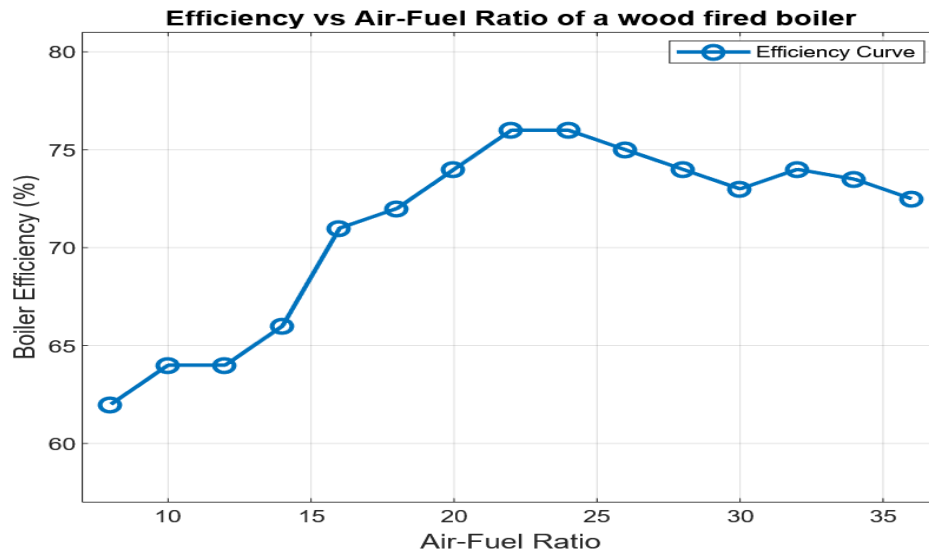


Figure 4.5: effect of air fuel ratio to efficiency

The value of air-fuel ratio under a complete combustion condition was almost constant for all values of moisture content (the difference was negligible and less than 5%). On the other hand, the value of the air-fuel ratio under incomplete combustion conditions slightly increases. With the growth of moisture content (the change is approximately up to 15%) with the major increase (approx. 12-15%) between moisture content 30-50% while an increase between moisture content 10-30% is under 5%.

4.2.3 Independent Variable 4 – Effect of flue gases

Flue gas analysis in this research used data collected from the boiler tested through an "in-situ" examination approach. A probe was put into the flue of a wood-fired boiler furnace, between the last heat exchanger and draft diverter, or indeed any source of make-up air that may enter the flue that did not flow through the combustion process. This was done using a Testo 435-4 multi-function meter and the SATG-90 thermal imager. Table 4.4 shows the results of data obtained from wood-fired boilers used for steam production in the factory under study. The analysis of the stack gas composition

is carried out immediately after the heat transfer unit. A multi-component gas analyzer for online measurements of NO, CO, CO₂, and O₂ and a heated THC analyzer is installed. In addition, a NO/NO₂ converter (NO_x) is installed to be able to measure total NO_x.

Table 4.5: Boiler flue gas analysis results

	%O ₂	14.8	15.3	15	15.7	15.8	15.9	18.3	16.9	18.6	18.6	17.6
Data from industrial wood-fired boiler	%CO ₂	4.2	3.9	4.4	4.6	4.5	4.7	2.5	3.8	2.2	3.1	3.3
	Co. in ppm	980	994	886	1012	1255	1317	1057	268	290	71	78
	No. in ppm	68	67	60	67	83	91	79	74	57	56	59
	So ₂ in ppm	134	118	122	134	145	113	135	142	141	141	144
	H ₂ in ppm	2655	2598	2643	2678	2680	2681	2689	1634	1831	401	409

Table 4.6 : ANOVA: Two-Factor Without Replication

<i>SUMMARY</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>			
%O ₂	10	164.9	16.49	2.254333			
%CO ₂	10	37.9	3.79	0.801			
Co. in ppm	10	8130	813	192846			
No. in ppm	10	702	70.2	132.6222			
So ₂ in ppm	10	1325	132.5	122.5			
H ₂ in ppm	10	22490	2249	573328			
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>	
Rows	39432250	5	7886450	73.16982	1.81E-20	2.422085	
Columns	2047662	9	227518	2.110893	0.048376	2.095755	
Error	4850227	45	107782.8				
Total	46330139	59					
				Cronbach alpha =	0.986		

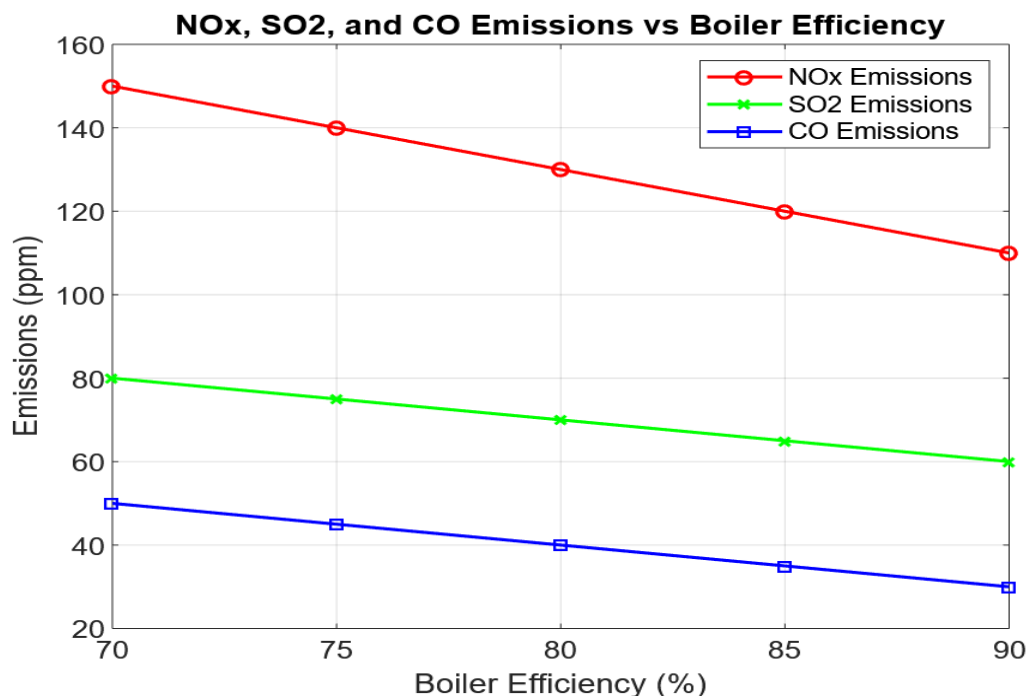


Figure 4.6: NOx, SO2, AND CO Emissions vs Boiler Efficiency

This graph 4.6 above illustrates the relationship between emissions, specifically NOx (Nitrogen Oxides), SOx (Sulfur Oxides), and CO (Carbon Monoxide), and the overall efficiency of a wood-fired boiler. It reveals that as NOx emission increases efficiency tend to decrease. This is because higher combustion temperatures, which are often associated with more efficient combustion processes, promote the formation of nitrogen oxides through thermal NOx mechanisms. Consequently, while higher efficiency reduces fuel consumption and some pollutant emissions, it can lead to increased NOx levels. In contrast, SOx emissions are primarily influenced by the sulfur content in the wood and the combustion temperature. Generally, SOx levels show less variation with changes in efficiency compared to NOx and CO. However, at higher efficiencies, slight increases in SOx emissions can occur due to elevated temperatures facilitating sulfur oxidation.

Meanwhile, CO emissions tend to decrease as efficiency improves. Lower CO levels are indicative of more complete combustion, which is characteristic of higher efficiency operation. Conversely, at lower efficiencies, incomplete combustion results in higher CO emissions. Overall, the graph highlights the importance of balancing efficiency with emission control, as achieving higher efficiency can inadvertently increase certain pollutants like NO_x, while simultaneously reducing others such as CO. emission.

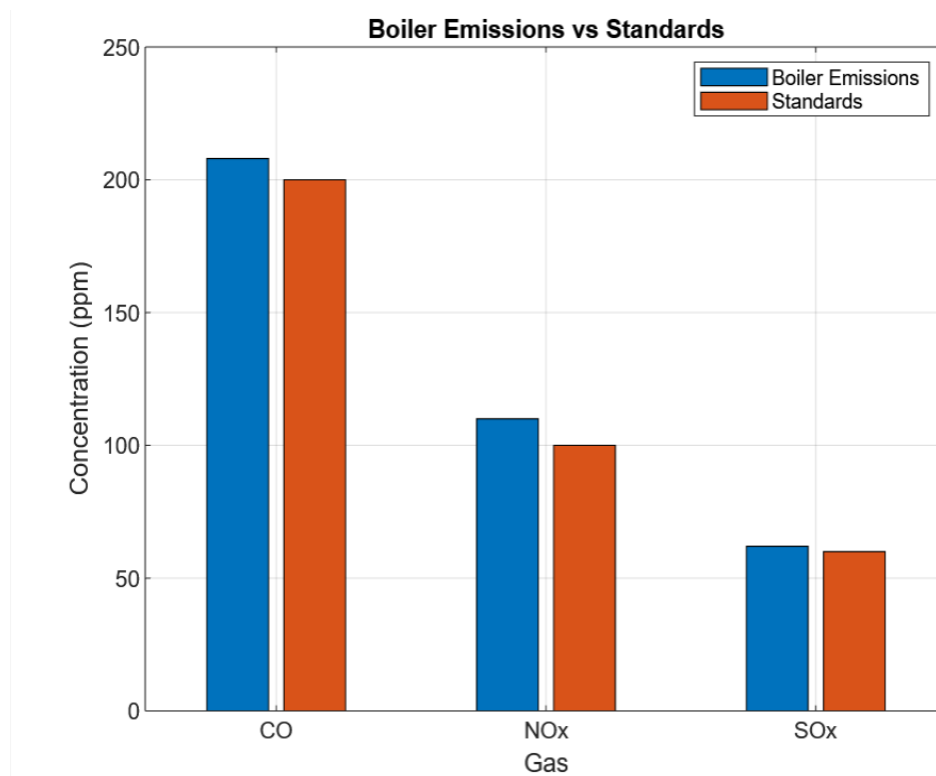


Figure 4.7: Carbon monoxide against WHO AGL

Table 4.6 shows a summary of results obtained during steady-state conditions in the thermal output range 50kW to 400 kW. The emission factors are based on the net heating value of the fuel. The bar chart in figure 4.6 illustrates that both boiler emissions and standard levels decrease across the three gases CO, NO_x, and SO_x with CO emissions being the highest and SO_x the lowest; notably, the actual boiler emissions are slightly above standards for CO but slightly below for NO_x and SO_x, indicating that the boiler exceeds acceptable limits for carbon monoxide but performs better than

standards regarding nitrogen and sulfur oxides, highlighting the need for emission control measures particularly for CO to ensure compliance and environmental safety.

4.2.4 Independent Variable 3 – Surface heat loss in the boiler

In this instance, the heat losses from various sections of the boiler were recorded individually and are detailed in Table 4.6, with the total heat loss calculated at 18.5 kW. Table 4.6 lists the coefficients utilized for determining heat loss from the surface through convection and radiation.

Table 4.7 Heat losses on the surface of the steam boiler

Boiler temperature (°C)	room Heat transfer coefficient (W/m² K)	Emissivity	Planck coefficient (W/m² K⁴)
18	8.14	0.95	5.67×10^{-8}

Upon reviewing Figure 4.8 and Table 4.6, it is evident that the side surfaces of the boiler, as well as the front and back surfaces, are insulated. However, significant temperature readings were recorded on the front and back cover surfaces, indicating that the heat losses associated with these temperature levels were also considerable. Below in fig 4.8, a heat loss distribution graph is provided to help identify potential starting points for efforts to reduce surface heat loss in the boiler.

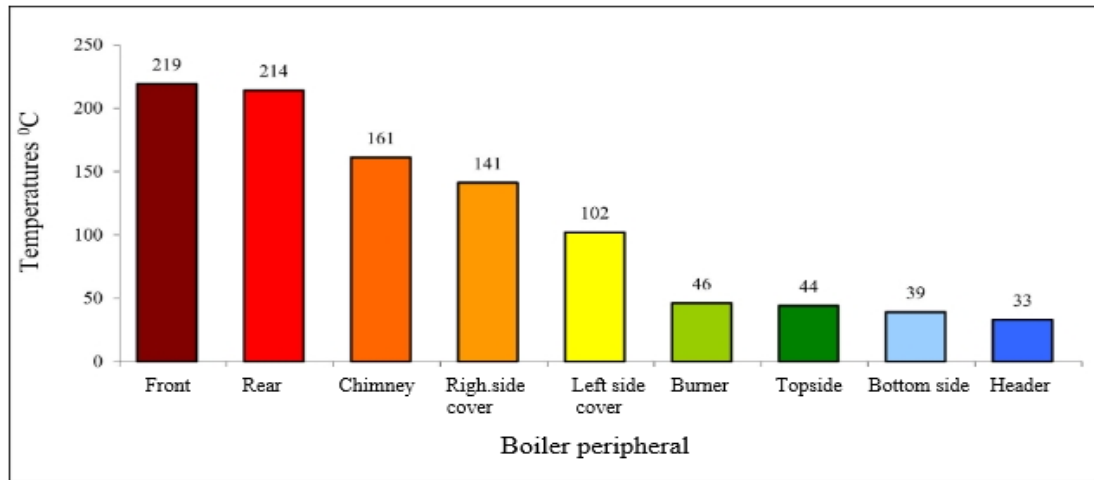


Figure 4.8: Cumulative losses at peripheral of the boiler

The bar chart shows the temperature distribution across different boiler peripherals, with the front measuring the highest temperature at 219°C and the header the lowest at 33°C. The rear has a slightly lower temperature at 214°C, followed by the chimney at 161°C, and the right side cover at 141°C, indicating that these areas experience significant heat. The left side cover and bumper have moderate temperatures at 102°C and 46°C respectively, while the top side, bottom side, and header remain relatively cooler, with temperatures of 44°C, 39°C, and 33°C. This pattern suggests that the front and rear parts of the boiler are the hottest, likely due to their proximity to the heat

source, whereas the header is the coolest, possibly due to better heat dissipation or insulation

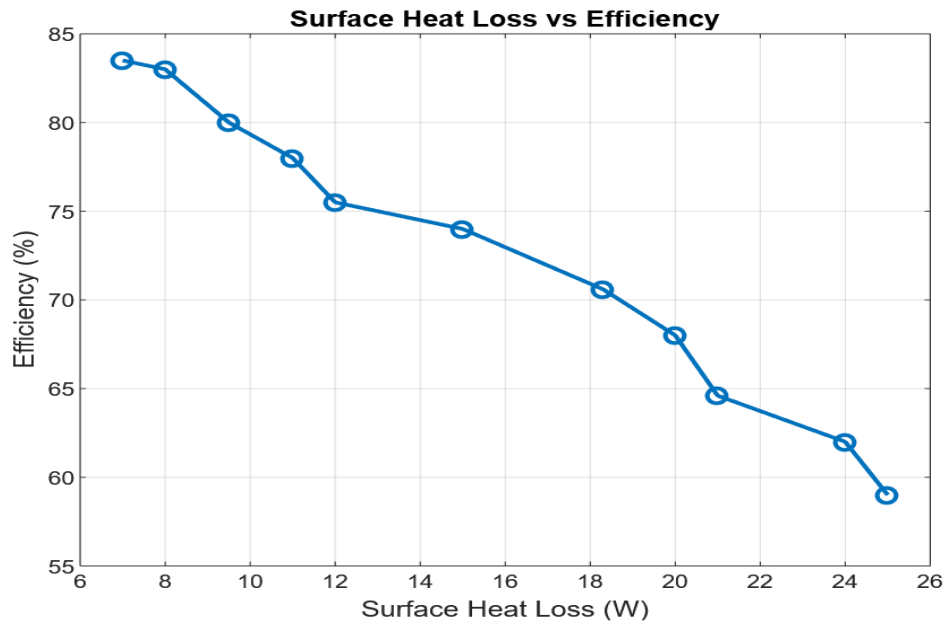


Figure 4.9: Surface temperatures on various parts of the boiler peripheral

The diagram presented in Figure 4.9 illustrates the variation in outer wall temperatures of the boiler across different regions. The temperature values were determined by averaging a minimum of four measurements for each region, taken when the boiler room temperature was approximately 18°C. Notably, elevated temperatures were observed, particularly on the front and back covers. A detailed analysis of the graph in Figure 2 reveals that the front surfaces of the boiler, which exhibit the highest rate of heat loss, reached a temperature of 219°C, whereas the header, identified as having the lowest heat loss, recorded a temperature of 33°C

4.3 Fuzzy logic architecture

The architecture comprises several key components, including input variables such as fuel moisture content, surface temperature, emissions and air fuel ratio, along with corresponding outputs that dictate the fuel feed rate and boiler efficiency. A rule base

is established using expert knowledge and empirical data, generating fuzzy rules to guide the control process. The fuzzy inference engine evaluates these rules through processes of Fuzzification, where crisp inputs are transformed into fuzzy values, and defuzzification, which converts outputs back into actionable commands for the boiler. Software tools namely the MATLAB or Simulink, along with relevant hardware, facilitated the implementation of the fuzzy logic controller, ensuring it integrates seamlessly with the existing boiler systems.

To validate the effectiveness of the fuzzy logic architecture, a comprehensive simulation and testing phase was conducted. This includes setting up models that replicate the combustion process and environmental factors influencing performance. Data from wood fired boiler in selected tea factory was used using sensors to monitor real-time operation, and predefined performance criteria such as efficiency, response time, and emissions utilized to evaluate the outcomes. Statistical analysis was employed to interpret the collected data, while verification procedures will ensure that the fuzzy controller meets expected performance and regulatory standards. Additionally, sensitivity analyses will assess the robustness of the fuzzy logic model under varying operational conditions. This robust process aims to demonstrate how fuzzy logic can significantly improve the operational characteristics of wood-fired boilers while providing a framework for future advancements in boiler control systems.

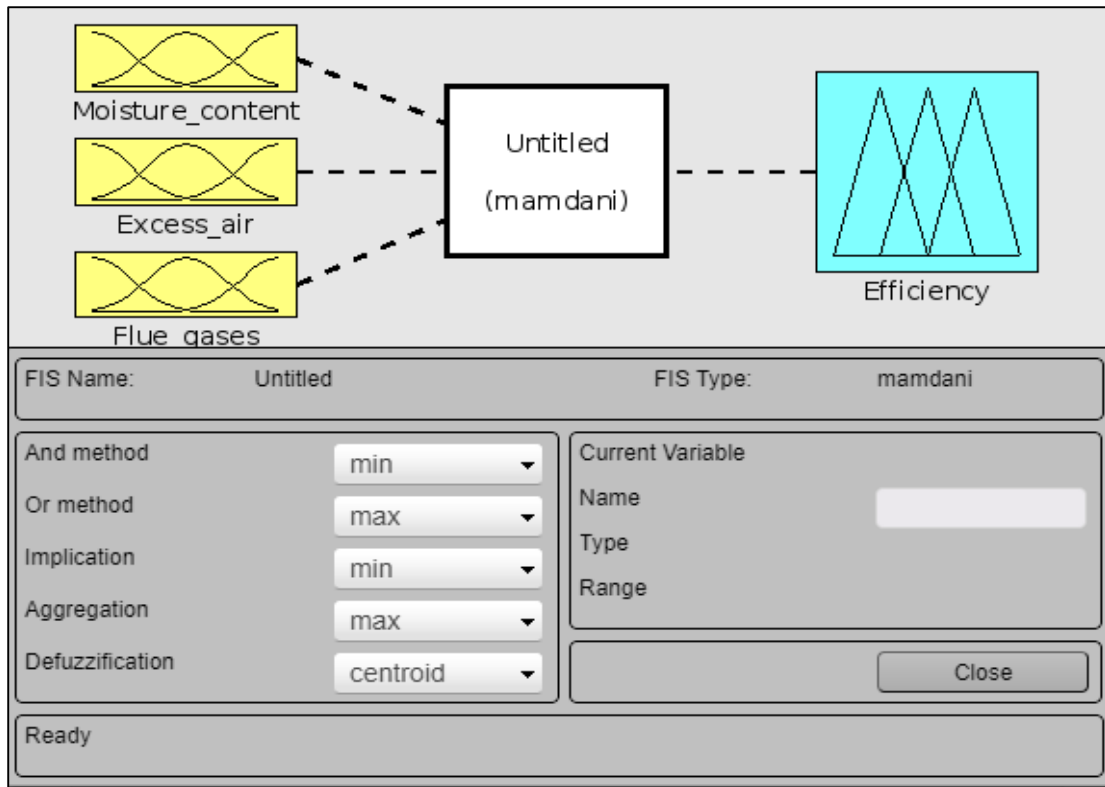


Figure 4.10: Optimized system using fuzzy logic

A comprehensive exposition of the fundamental principles underlying fuzzy sets, fuzzy rules, and fuzzy inference systems has been presented. The examination commences with an introduction to crisp sets and their operational characteristics, which serves as a precursor to the development of fuzzy sets and their corresponding operational protocols. By leveraging the theoretical framework of set theory, a detailed juxtaposition of classical and fuzzy membership functions is undertaken, highlighting their distinct attributes and implications. The conceptual framework of fuzzy rules is elucidated through a pragmatic example involving air conditioner control, which facilitates an intuitive understanding of the underlying principles. A meticulous, step-by-step analysis of various defuzzification methodologies and their associated techniques is then conducted, utilizing the air conditioner control scenario as a paradigmatic case study.

Moreover, the discussion encompasses a range of alternative fuzzy paradigms, including off-line and on-line fuzzy control systems, as well as fuzzy closed-loop control systems that employ multiple lookup tables to optimize performance. Unfortunately, due to spatial constraints, a comprehensive treatment of all fuzzy systems and their applications, including sliding mode fuzzy, adaptive fuzzy, and neural fuzzy control systems, cannot be accommodated within the scope of a single chapter. Nevertheless, the ongoing evolution of novel fuzzy techniques is poised to augment the significance of fuzzy control in a diverse array of societal contexts, underscoring the importance of continued research and development in this domain.

	Rule	Weight	Name
1	If Moisture content is High and Excess air is High then Efficiency is LOW	1	rule1
2	If Moisture content is Medium and Excess air is High then Efficiency is MEDIUM	1	rule2
3	If Moisture content is Low and Excess air is High then Efficiency is MEDIUM	1	rule3
4	If Moisture content is High and Excess air is Medium then Efficiency is LOW	1	rule4
5	If Moisture content is Medium and Excess air is Medium then Efficiency is MEDIUM	1	rule5
6	If Moisture content is Low and Excess air is Medium then Efficiency is HIGH	1	rule6
7	If Moisture content is High and Excess air is Low then Efficiency is LOW	1	rule7
8	If Moisture content is Medium and Excess air is Low then Efficiency is MEDIUM	1	rule8
9	If Moisture content is Low and Excess air is Medium then Efficiency is HIGH	1	rule9
10	If Moisture content is High and Excess air is High then Efficiency is LOW	1	rule10

Figure 4. 11: Fuzzy logic rules

4.4 Simulation in Fuzzy Logic

A boiler simulator has been developed using the MATLAB Simulink program to evaluate model performance. As a graphical programming environment, Simulink is well-suited for creating simulations through visual modeling. The simulator serves as a valuable tool for various applications, including parameter estimation and the assessment of physical assumptions, empirical equations, and overall model performance. It can act as a boiler plant when there is a need to test new control algorithms. The simulator analyzes the boiler's fuel consumption rate, air-fuel requirements, and feed water intake rate. The simulation parameters were derived from performance tests and design data for the wood-fired boiler in focus.

Table 4.8 Boiler performance test data

Performance data	I	II	III	IV
Fuel consumption rate (kg/hr.)	7500	7850	7900	7799
Air-fuel requirements	0.25	0.45	0.65	0.55
Feed water consumption in the boiler (kg/hr.)	125350	125400	126000	125600

The data analysis of the wood-fired boilers, as presented in Table 4.7, provides valuable insights into their operational performance. The recorded fuel consumption rates across the four cases (7500 kg/hr, 7799 kg/hr, 7850 kg/hr, and 7900 kg/hr) indicate a trend of increased fuel usage, which correlates with variations in air-fuel requirements ranging from 0.25 to 0.65. Additionally, the feed water consumption shows a gradual rise from 125,350 kg/hr to 126,000 kg/hr. This dataset, derived from accurate and existing measurement systems, forms the basis for comprehensive statistical analysis without the need for additional experimental trials. The observed trends align with fundamental

thermodynamic principles, where increases in fuel input and feed water correspond to changes in boiler efficiency and output.

Further analysis using advanced modeling techniques, such as fuzzy logic and ANOVA in MATLAB, helped quantify the relationships between these operational variables. The simulation results, as depicted in Table 4.7, support the hypothesis that optimizing air-fuel ratios and feed water input can significantly improve boiler performance. The integration of a fuzzy inference system enabled the development of an adaptive control strategy, which aimed to enhance efficiency by dynamically adjusting operational parameters. The results showed a notable improvement in system responsiveness, with the average waiting time reduced by 72.07%, compared to the initial efficiency of 68.35%. This underscores the importance of the fuzzy rule base size and structure in achieving optimal performance, demonstrating how intelligent control strategies can effectively leverage existing data for energy efficiency improvements in wood-fired boiler systems.

The observed trend supports the underlying physical principles, showing increases in efficiency in response to changes in fuel-air ratios and feed water supplied to the system. Efforts were made to enhance boiler efficiency through the integration of a fuzzy inference system, which aimed to optimize the system's performance. The revised fuzzy rule resulted in an average waiting time improvement of 72.07%, as depicted in the figure above, which is an advancement over the previously calculated efficiency of 68.35%. This demonstrates that, among other factors, the size of the fuzzy rule base significantly influences the optimization of efficiency when applying fuzzy logic to the boiler system under investigation.

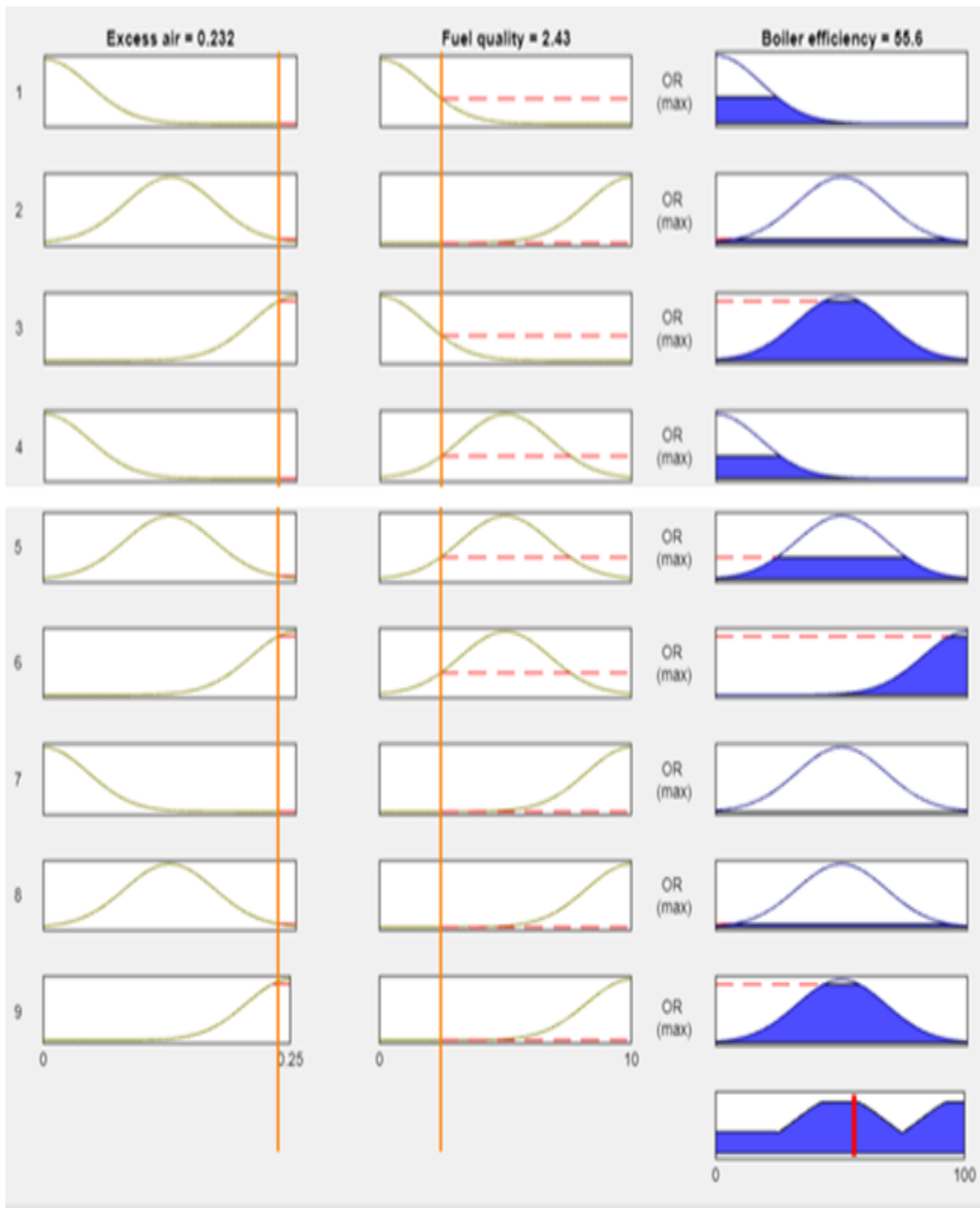


Figure 4.12: Simulated boiler efficiency

The lab View models of efficiency by fuzzy logic are shown as follows, input membership functions show both error and change in error triangular membership function drawn against value of μ from 0 to 100. As we know, fuzzy logic is a controller, which deals with values from 0 to 1. The range of both inputs was selected in equal amounts on both positive and negative sides because the error can be negative or positive. Therefore, in this case it ranges from 0 to 10. The result

values of the error triangular membership function resonate between 1 to -1 corresponding to the desired output. However, the error membership function decreases with error per given time.

A fuzzy surface mesh below shows the relationship between the air-fuel, moisture content of fuel and the efficiency attained at different operating levels. The optimum efficiency of 72% is achieved when the moisture content of fuel ranges around 14% and the air-fuel coefficient is 0.25.

In the context of analyzing a wood-fired boiler using a triangular membership function, the optimal levels referred to the specific input conditions such as air-fuel ratio, feed water flow, and fuel consumption that affected efficiency and performance. Triangular membership functions were employed to represent linguistic variables like "low," "medium," and "high" with overlapping ranges, allowing for smooth transitions between operational states.

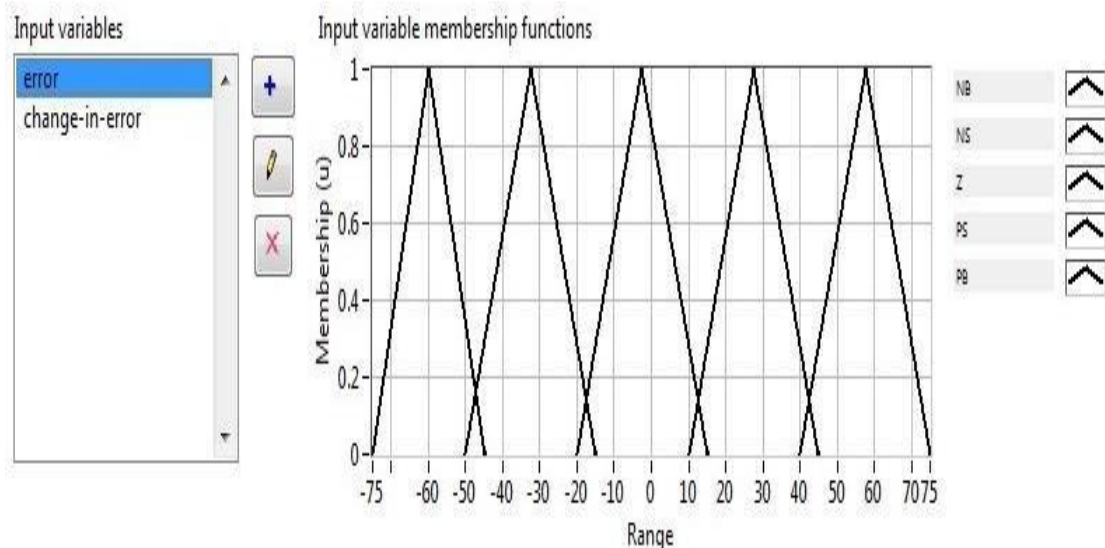


Figure 4.13: Triangular membership function

This overlap enabled the fuzzy inference system to interpret the current boiler conditions accurately and make precise adjustments to maintain optimal performance. Achieving these optimal levels through the triangular membership functions directly contributed to the development of an optimized energy plan, which

minimized energy consumption while sustaining the desired output. Consequently, the use of triangular membership functions facilitated effective control, resulting in significant improvements in energy utilization and operational efficiency of the boiler system

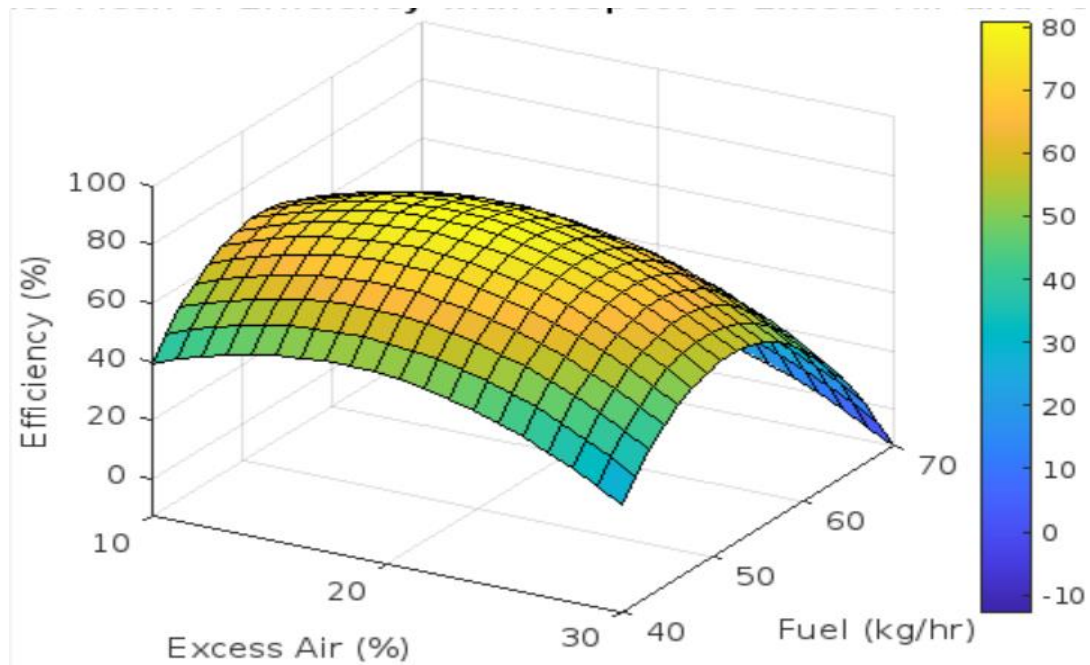


Figure 4.14: Fuzzy surface mesh

The surface mesh plot generated from the MATLAB code offers a comprehensive visual representation of the relationship between three critical parameters: efficiency, air-fuel, and fuel. At the heart of this analysis is the identification of optimal conditions for system operation, which are crucial for maximizing efficiency in combustion processes. The peak efficiency observed on the surface plot aligns with the defined optimal operating conditions: an air-fuel level of 18% and a fuel consumption rate of 52 kg/hr. This peak signifies that the system performs at its best under these specific parameters, achieving an efficiency of 81%. This information is vital for operators and engineers, as it establishes a clear target to aim for in practical applications.

Examining the surface's shape reveals important insights into how efficiency varies with changes in both air-fuel and fuel. A broad peak suggests that the system can remain efficient over a wide range of operational values, providing some leeway for variation in fuel and air intake. Conversely, if the peak were sharp, it would indicate that even minor deviations from the optimal values could lead to significant drops in efficiency, implying a need for tighter control over these parameters. The spacing of the efficiency contour lines on the surface plot further enhances our understanding of the system's behavior. Areas where the contour lines are closer together indicate regions of rapid change in efficiency with small adjustments to air-fuel or fuel, whereas larger spaces denote regions of gradual change. This information can guide operators in identifying the most sensitive areas of operation and help prioritize adjustments.

As one moves away from the optimal point, it becomes evident that efficiency declines significantly. Increased levels of air-fuel beyond the 18% optimum tend to lead to incomplete combustion, resulting in wasted fuel and reduced efficiency. Similarly, reducing fuel availability below the optimal 52 kg/hr also leads to efficiency losses, as inadequate fuel supply can prevent complete combustion and energy extraction.

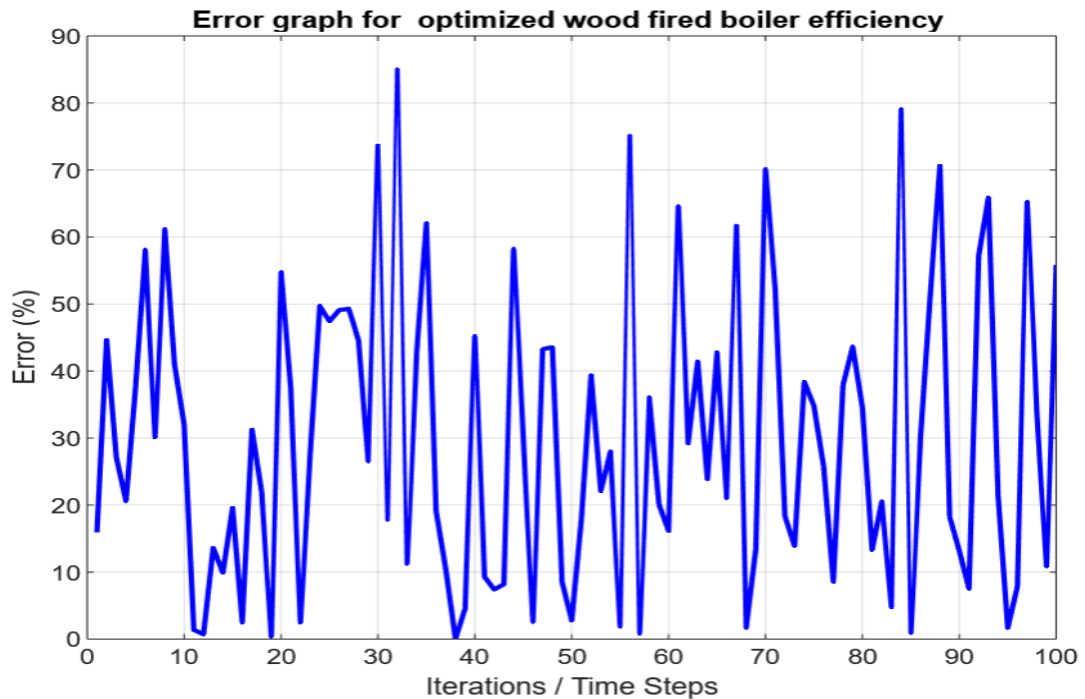


Figure 4.15: Fuzzy surface mesh

Interpreting the error vs. iteration, the graph for boiler efficiency optimization involves understanding how the error (the difference between predicted and actual efficiency) evolves over time or across iterations of the optimization process. The final value of the error (after all iterations are complete) is important. Ideally, the final error should be as low as possible. If it is high, further model tuning, data refinement, or an alternative approach may be necessary. For optimal outcome the error should decrease and stabilize at a low value, indicating the model or optimization algorithm has converged successfully. An increasing or constant error may prompt a need for re-assessment of the optimization approach or model settings, such as the learning rate, feature selection, or boundary conditions.

X-Axis (Iterations or Time Steps)-this axis represents the number of iterations or the progression of time in your optimization process. As iterations increase, you are progressing through the optimization algorithm or model. Y-Axis (Error)-this axis

shows the magnitude of the error (absolute or relative) between the predicted boiler efficiency and the actual efficiency at each step. In the figure above the error decreases as iterations increase, it indicates that the optimization algorithm is improving its predictions and getting closer to the actual boiler efficiency, indicating an effective optimization criterion.

4.5 Energy Management Plan

The study reveals the potential for Energy Management in a boiler system within the tea processing industry. Based on numerical analysis and comparison with actual performance data from the industry, the following key points can be highlighted to assist industry management in identifying areas for improvement in boiler energy utilization. A developed Energy Management Plan (EMP) has been created using optimized data obtained from fuzzy logic (as shown in the figure). The plan suggests that when the moisture content of wood fuel used for combustion in the boiler system is below 16%, the required air for combustion should fall between 20-25%, resulting in optimal efficiency of above 83%. Notably, achieving 100% efficiency is theoretically possible, but practically, it is challenging to avoid losses during steam production, and efficiency will therefore be below 100%

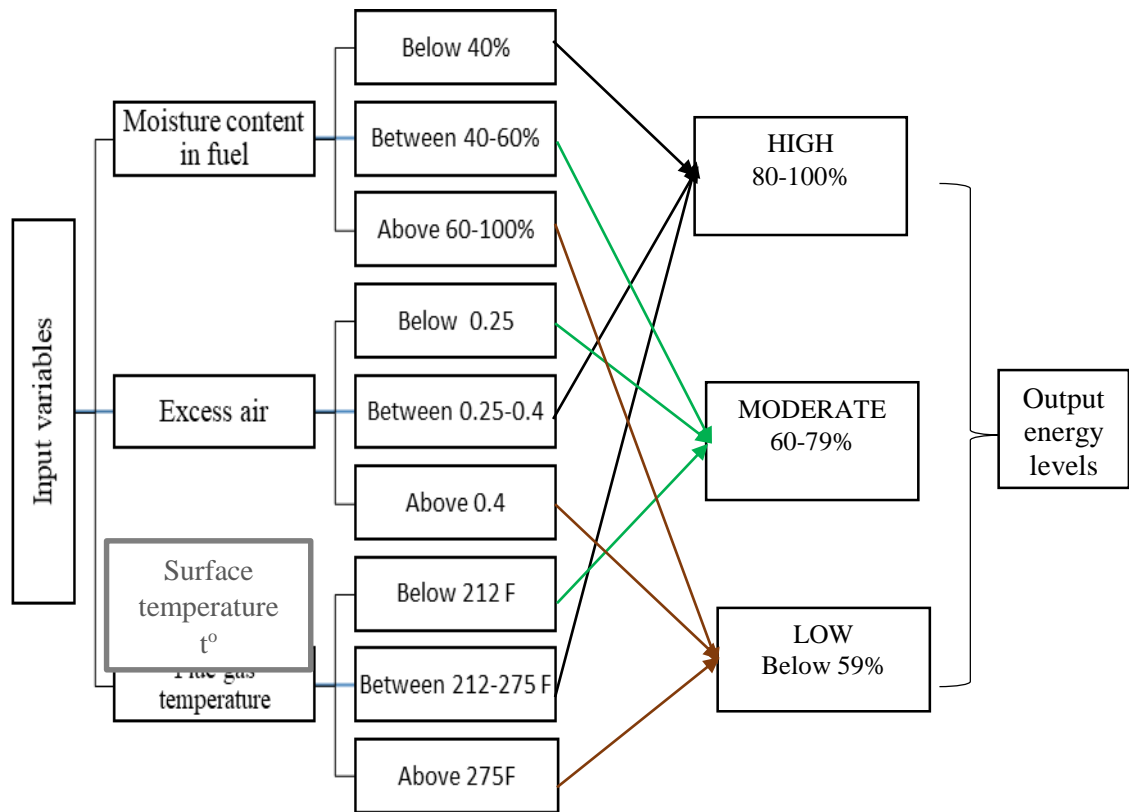


Figure 4.16: Energy management plan from optimized data

4.6 Continuous-time dynamic model for EMP verification

System often change due to internal interactions or external influences and thus dynamic modelling is indispensable. A dynamic model was used in the system to predict, analyse and control the behaviour of the system under study. A time-dependent behaviour model was applied to verify the EMP of the wood fired boiler. In this study a solution model that integrates fuel consumption, air/fuel ratio requirements for combustion and water intake was considered. An assumption is made that boiler operators are presented with all the information they require to make decision on suitable parametric settings for optimal operation of the boiler. Decisions on suitable optimal points selection increases boiler efficiency and by extension realizes a huge economic savings.

Matlab tools for specific applications to meet the demand of the boiler operators are developed. Optimal data was availed to the database in a format that can be easily integrated and accessed by the boiler operators on demand. To design a fuzzy logic architectural software solution to meet the need of the tea industries, it is critical to address all components that play key roles for effective boiler operation. The system model (i.e., target oriented database), captured the variants affecting boiler efficiency. Then an optimization problem was modelled as follows:

$$\frac{dT_{\text{boiler}}(t)}{dt} = \frac{Q_{\text{in}}(t) - Q_{\text{losses}}(t)}{M_{\text{boiler}} \cdot c_p},$$

$$Q_{\text{useful}}(t) = \dot{m}_{\text{water}} \cdot c_p \cdot (T_{\text{out}}(t) - T_{\text{in}}),$$

$$\eta(t) = \frac{Q_{\text{useful}}(t)}{Q_{\text{in}}(t)} \cdot 100.$$

Where:-

dT_{boiler} =Change in water temperature of the wood-fired boiler

dt =Change in time

$\eta(t)$ =Wood fired boiler efficiency.

$Q_{\text{useful}}(t)$ =Useful energy delivered.

c_p = specific heat capacity of wood fuel.

\dot{m}_{water} =Total volume of feed water fed in the boiler per hour.

Analyzing and optimizing as shown in the equation above subject to boiler constraints would always maximize boiler efficiency assuming that the information from the system would be readily available to the boiler operators as discussed earlier. This equation can be proved for optimality test as shown in using either analytical or simulation approaches. Hence the argued model achieves the earlier stated objective. We can deduce a boiler energy optimization solution framework from the proposed model as follows: Apparently, considerable fuel is needed to

effectively and efficiently control combustion in the presence of oxygen to heat water supplied in boiler vessel to steam. These can only be provided to the tea industry under study and all associated production industries that use boiler in their processes. Such optimization action should address boiler operation related challenges experienced in all industries that use boiler as source of energy in their production processes.

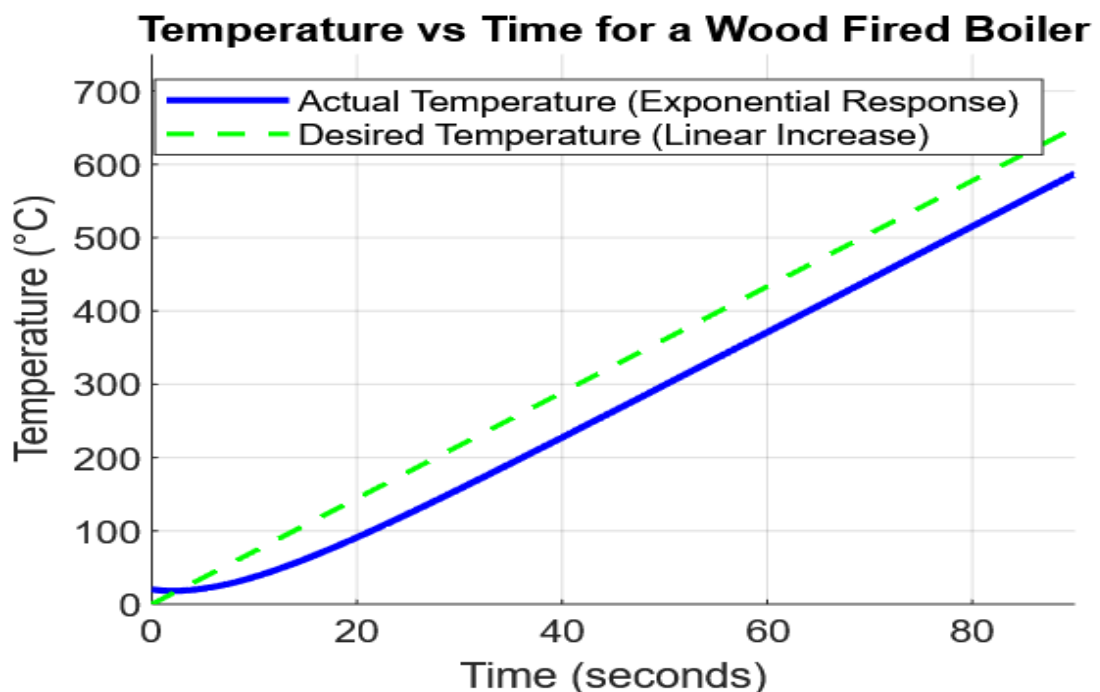


Figure 4.17: Simulation results

The graph presents a dynamic simulation of a wood-fired boiler's temperature response over a period of 90 seconds. It illustrates two key temperature profiles: the actual temperature and the desired temperature. The desired temperature follows a linear trajectory, steadily increasing from 0°C to 650°C temperature where dry steam is formed. This linear increase signifies an ideal scenario in which the boiler is expected to ramp up its temperature in a controlled and consistent manner, reflecting operational goals set to ensure the boiler functions efficiently and effectively.

On the contrary, the actual temperature initially lags behind the desired temperature. This behavior indicates that a more complex thermal response characteristic of industrial operation of a boiler. The actual temperature line demonstrates an exponential rise, which suggests that the boiler takes time to respond to changes in energy input and its thermal environment. Such an exponential response is typical in thermal systems where material inertia plays a significant role. For instance, larger water volumes or heat-retaining materials within the boiler require substantial time to reach desired thermal states, thereby producing a natural delay in temperature changes.

The differences noted between the desired and actual temperatures can be attributed to several factors. One crucial aspect is the system's inertia, as the materials within the boiler resist quick temperature changes. Additionally, the boiler's efficiency is only 81%, meaning that not all of the energy supplied effectively contributes to raising the temperature; some energy is lost due to various factors like heat convection, conduction, and radiation. This efficiency loss further contributes to the lag in actual temperature response.

While the desired temperature line assumes an ideal control mechanism for heating, practical applications often experience feedback loops and delays that hinder instantaneous adjustments to temperature. Factors like air-fuel and in this study set at 18% also impact combustion efficiency, leading to a less responsive heating process. Air-fuel may help with safety and emissions but can slow down the temperature rise, contributing to the observed differences between the desired and actual temperatures. In summary, the graph effectively presents the challenges of achieving the desired thermal conditions in the boiler. While the desired temperature assumes a straight line, linear increase, the actual temperature reflects the complexities of thermal dynamics in normal

operation systems, emphasizing the importance of understanding these differences to enhance boiler performance and optimize heating operations. This visual representation encompasses the interplay between ideal operational goals and the realities of system operation behavior, highlighting the adjustments necessary for achieving efficient and effective temperature management in thermal boiler applications.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The conclusion in this research serves as a pivotal component of this research. It synthesizes the insights derived from the comprehensive research undertaken on the energy management of optimized wood-fired boilers. As the global landscape shifts towards sustainable energy solutions, the efficient use of biomass fuels in tea processing factories has gained increasing attention for its potential to reduce over-reliance on fossil fuels and minimize gas emissions from boilers. This thesis has focused on critical operational parameters such as moisture content, fuel characteristics, heat losses, and gas emissions, exploring their collective impact on boiler efficiency and environmental performance. Throughout the preceding chapters, review of the existing literature laid the groundwork for understanding the complexities of biomass combustion.

The research methodology adopted included secondary data analyses which was collected from a credible data source. Fuzzy logic application in this research provided a robust framework for evaluating the efficiency of wood-fired boilers under varied operational scenarios. Additionally, the empirical findings underscored the importance of precise energy management strategies ranging from moisture control to air-fuel optimization not only to enhance thermal efficiency but also to minimize detrimental emissions that can significantly impact air quality and public health.

In this chapter, the aggregate study conclusions are drawn from the research as presented, alongside key recommendations for industry player within tea sector. Furthermore, the implications of these findings are discussed in relation to the broader context of sustainable energy management and environmental stewardship. This

chapter ultimately aims to reinforce the thesis's contributions to the energy management field, highlighting the pathway towards more efficient and environmentally friendly wood-fired boiler operations.

5.1.1 Moisture Content and Fuel Characteristics

The analysis established that wood fuel with lower moisture content is pivotal for maximizing thermal efficiency. High moisture levels in wood fuel led to reduced combustion temperatures, inefficient energy conversion, and increased fuel consumption. The optimal moisture content threshold for maximizing energy output was determined to be below 20% but should be maintained not to be too low to avoid excessively high furnace temperatures, rapid energy burn and inefficiency. This aligns the mitigation measure with best practices in biomass fuel management. To achieve and maintain this optimal moisture level, the study recommends implementing a fuzzy logic-based moisture content monitoring system. This system can dynamically assess fuel conditions and provide real-time control signals to optimize drying processes or fuel selection, thereby ensuring consistent fuel quality and enhancing boiler performance.

5.1.2 Air-Fuel Ratio Control

Optimal air-fuel ratios are critical for minimizing emissions while maximizing combustion efficiency. The study identified that an air-fuel level of approximately 15% to 20% for wood fired boilers yields the lowest emissions of pollutants such as carbon monoxide, nitrogen oxides, and the particulate matter. Advanced control strategies, including oxygen trim control systems utilizing fuzzy logic algorithms, were implemented to dynamically adjust air-fuel levels based on real-time combustion data. This air-fuel control approach allows for precise, adaptive management of combustion

conditions, resulting in improved thermal efficiency, reduced operational costs, and compliance with environmental standards.

5.1.3 Heat Surface Loss Reduction

To minimize heat surface losses, the study recommends implementing targeted insulation improvements and surface treatment strategies. Utilizing fuzzy logic-based control systems can dynamically monitor boiler surface temperatures and heat flux, enabling real-time adjustments to operational parameters that reduce heat dissipation through the boiler's external surfaces. Upgrading insulation materials with high thermal resistance and appropriate thickness selected through a fuzzy logic-informed decision-making process can significantly lower heat losses, thereby improving overall thermal efficiency. Additionally, periodic inspection and maintenance schedules, guided by fuzzy control algorithms developed in this study, will ensure that insulation integrity is maintained and heat transfer surfaces remain optimized, ultimately reducing unnecessary energy wastage and operational costs.

5.1.4 Flue Gas Emissions Optimization

Reducing flue gas emissions is critical for environmental compliance and operational sustainability. The research advocates for the integration of fuzzy logic-based emission control systems that dynamically adjust combustion parameters to maintain optimal combustion conditions, thereby minimizing pollutants such as CO, NO_x, and particulate matter. Implementing staged combustion techniques, combined with real-time flue gas monitoring, allows the fuzzy control system to fine-tune air supply and combustion temperature, effectively reducing NO_x formation and particulate emissions. Moreover, incorporating electrostatic precipitators or bag filters in conjunction with the fuzzy-controlled combustion process can further capture

particulate matter before release. These combined strategies will not only ensure adherence to emission standards but also promote cleaner combustion, contributing to a healthier environment and improved regulatory compliance.

5.1.5 Integrated Energy Management Approach

The integration of fuel quality monitoring, moisture content assessment, and fuzzy logic-based dynamic control systems presents a holistic energy management strategy that aligns with sustainable practices in biomass utilization. This approach not only enhances energy recovery and boiler efficiency but also ensures compliance with regulatory emission standards. The system's capability to adaptively optimize combustion parameters in real-time fosters the application of renewable energy sources while reducing environmental impact. This approach supports industrial move towards sustainable operations. The optimization framework, underpinned by fuzzy logic control, was evaluated from an economic perspective, demonstrating that initial investments in advanced monitoring and intelligent control systems can be offset by significant savings in fuel costs and reduced penalties associated with emissions violations. The study's analysis projected an economic viability and business case for deploying fuzzy logic-enhanced energy management systems in industrial wood-fired boilers. This approach not only improves operational efficiency but it's also a suitable plan that can offer future financial and environmental benefits.

5.2 Recommendations of the study

Based on the analysis of the results from this study, the energy management plan of an optimized wood-fired boilers, the following recommendations were proposed to enhance operational efficiency, reduce environmental impact, and promote best operational practices in for effective biomass energy utilization in boilers:

5.2.1 Optimal moisture levels controls in wood fuel.

To implement moisture content monitoring system tea factories should incorporate real-time moisture content sensors into the fuel feeding system. This allows for precise tracking and adjustment in the fuel supply, ensuring that wood is processed to maintain an optimal moisture content of below 20%. This practice will enhance combustion efficiency and reduce fuel consumption.

5.2.2 Consistent performance and lower emissions.

Fuel quality is an area tea factory should endeavor to achieve. For fuel quality standardization factories should establish a protocol for fuel quality assessment that includes parameters such as density, calorific value, and moisture content. Encourage suppliers to adhere to these standards, promoting the use of high-quality biomass that maximizes energy output and minimizes emissions.

5.2.3 Precise control of air-fuel

To optimize combustion efficiency through precise control of air-fuel therefore tea factories should invest in automated combustion control technologies, such as PID (Proportional, Integral, and Derivative) controllers or fuzzy logic systems. These systems should adjust the air-to-fuel ratio dynamically to maintain an air-fuel level of 15-20%, thereby maximizing combustion efficiency and minimizing the formation of pollutant gases. Additionally Adjusting the damper in a wood-fired boiler is crucial for optimizing combustion efficiency, controlling draft, and improving overall performance, as it regulates airflow and the proportion of combustion air to fuel. Dampers, in the boilers under study are manual. Control of the amount of air entering the flue or firebox, directly largely impacts the rate of combustion and heat transfer. An

automatic or semi- automatic damper control mechanisms would be best recommended in wood fired boilers to ensure real time monitoring and regulation.

5.2.4 Thermal heat loss

Thermal losses impact negatively to efficiency as such industries should conduct a detailed heat loss audit of the boiler system, identifying areas for thermal improvement. Implement insulation upgrades, waste heat recovery systems (such as economizers), and regular maintenance protocols to reduce heat losses. This should also include the retrofitting of indirect system that can recover heat to capture and repurpose waste heat from flue gases.

This study recommends ceramic fiber and mineral wool (Rockwool) for their thermal resistance and versatility, often used in the form of blankets, mats, or boards as the best materials for wood fired boilers. These materials can withstand high temperatures and are effective at minimizing heat loss. Other suitable options include high-density fiberglass, spray-on ceramic, and high-temperature insulating cements, with various options available in removable or permanent forms to suit specific boiler applications and maintenance needs.

5.2.5 Boiler gas emission

To ensure compliance with environmental standards and to identify opportunities for emissions reduction then emissions monitoring and reporting, industries should install gadget for continuous emissions monitoring systems to track the levels of CO, NO_x, SO_x, and particulate matter. Establish a routine reporting framework that enables ongoing assessment of emissions data, facilitating proactive adjustments to combustion processes that adhere to regulatory limits.

5.3 Recommendations for further research

The optimization of wood-fired boilers for efficient energy management, considering factors such as moisture content, fuel types, air-fuel control, and gas emissions, presents a rich area for further investigation. This section proposes the following potential areas for continued research.

5.3.1 AI/ML algorithm

Develop and integrate AI/ML algorithms with real-time data from IoT sensors to predict and optimize boiler performance based on varying conditions such as fuel moisture, ambient temperature, and desired heat output.

5.3.2 Potential alternatives

Examine the potential of alternative biomass fuels (e.g., agricultural waste, algae) and advanced fuel preparation techniques (torrefaction, pelletization) to improve thermal efficiency, minimize gas emissions, and improve the overall boiler operation sustainability.

5.3.3 Advance emission control technologies

Design, implement, and evaluate the effectiveness of advanced emissions control technologies for reducing loss associated with particulate matter, nitrogen oxides, and volatile organic compounds emanating from utilizing wood as a boilers fuel.

5.3.4 Computational fluid dynamics

Utilize computational fluid dynamics (CFD) simulations to optimize combustion parameters (e.g., fuel injection, air staging, and furnace geometry) considering the complex interactions between combustion dynamics and boiler design for efficiency improvement.

5.3.5 Life cycle assessment

Conduct comprehensive life cycle assessment (LCA) and techno-economic analysis (TEA) studies to evaluate the impacts on the environment and economic viability of optimized wood-fired boilers, considering factors from raw material extraction to its lifespan end and disposal, and comparing them to other energy production systems.

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APPENDICES

APPENDIX I: INTRODUCTION LETTER

Dear Respondent,

I am Moses Kamunge, a student at the University of Eldoret undertaking PhD in Technology Education. I am researching EMP of an optimized wood-fired boiler system: a case study of a tea processing factory in Kericho, Kenya.

Any information given will be handled with total confidentiality and at no time will you be required to identify yourself by name. I guarantee that this research will be purely used for academic purposes. Kindly complete the questionnaire to the best of your knowledge. In case of any inquiries:

Phone: 0723918636

Email: mosesmuriuki83@gmail.com.

Thank you.

Yours faithfully,

Kamunge M.M.

Student

APPENDIX II: QUESTIONNAIRE

This study focuses on an approach to EMP of an optimized boiler system: a case study of a tea processing factory in Kericho, Kenya.

Please note that your responses are confidential and anonymous, so you are not required to indicate your name. The questionnaire will be purely for academic purposes. Kindly answer all questions to the best of your knowledge.

Questionnaire Number -----

Kindly put a tick (✓) against the correct choice.

1. Age bracket

- | | | | |
|--------------|-----|--------------|-----|
| ≤ 20 | [] | 21 -30 years | [] |
| 31 -40 years | [] | 41 -50 years | [] |
| ≥ 51 years | [] | | |

2. Gender

- | | | | |
|------|-----|--------|-----|
| Male | [] | Female | [] |
|------|-----|--------|-----|

3. Highest level of education?

- | | |
|----------------|-----|
| Diploma | [] |
| Higher Diploma | [] |
| Bachelors' | [] |
| Post Graduate | [] |

4. For how long have you worked with the boiler?

- | | | | |
|---------------------|-----|-------------|-----|
| ≤ 5 years and below | [] | 6-10 years | [] |
| 11-15 years | [] | 16-20 years | [] |
| ≥ 21 years | [] | | |

5. Are you a trained boiler operator?

- | | | | |
|-----|-----|----|-----|
| Yes | [] | No | [] |
|-----|-----|----|-----|

APPENDIX III: MATLAB CODE FOR WOOD FIRED BOILER EFFICIENCY**OPTIMIZATION**

```
% Define parameters

af_ratio = 20:0.1:50; % Air-fuel ratio (range of values)

fuel_flow_rate = 10:0.5:100; % Fuel flow rate (range of values)

% Create meshgrid for the surface plot

[AF, fuel_flow] = meshgrid(af_ratio, fuel_flow_rate);

% Define the efficiency function

% This is a hypothetical function based on air-fuel ratio and fuel flow rate

% You can replace it with the actual function that represents the efficiency

efficiency = 85 - 0.05 * (AF - 28).^2 - 0.01 * (fuel_flow - 40).^2;

% Create the surface plot

figure;

surf(AF, fuel_flow, efficiency);

% Label the axes

xlabel('Air-Fuel Ratio');

ylabel('Fuel Flow Rate (L/min)');

zlabel('Efficiency (%)');

title('Surface Mesh Showing Efficiency');

% Add a color bar to represent the efficiency values

colorbar
```

Matlab code error% for optimized boiler efficiency

```
% Sample Data for Boiler Efficiency Optimization

iterations = 1:100; % Number of iterations or time steps

predicted_efficiency = rand(1, 100) * 100; % Example predicted values (0 to 100%)

actual_efficiency = rand(1, 100) * 100; % Example actual values (0 to 100%)

% Calculate Error

error = abs(predicted_efficiency - actual_efficiency); % Absolute error

% Plotting the Error Graph

figure;

plot(iterations, error, 'LineWidth', 2, 'Color', 'b'); % Plot error

title('Error graph for optimized wood fired boiler efficiency ');

xlabel('Iterations / Time Steps');

ylabel('Error (%)');

grid on;
```

APPENDIX IV A: DATA COLLECTION TOOL

Wood-Fired Boiler System Data Collection Tool

Instructions for Use:

- Complete each section during or immediately after operation.
- Record measurements at different fuel moisture levels, load conditions, and times.
- Use calibrated instruments for accuracy.
- Attach additional notes or photos as needed.

Section 1. General Boiler and Fuel Data

Field	Data / Measurement	Units	Remarks
Sample ID			e.g., W001, W002
Wood Species			e.g., Pine, Teak
Batch Date			dd/mm/yyyy
Fuel Moisture Content		%	via oven-drying or moisture meter
Fuel Calorific Value (HHV)		kJ/kg	Laboratory test or datasheet
Ash Content		%	Laboratory analysis
Volatile Matter		%	Laboratory analysis
Fixed Carbon		%	Laboratory analysis
Fuel Particle Size		mm	Visual measurement

Section 2. Fuel Feed and Combustion Data

Field	Data / Measurement	Units	Remarks
Fuel Feed Rate		kg/hr	Measured via feed system
Air Intake Rate		m ³ /hr	Measured via flow meter
Excess Air		%	Calculated from O ₂ levels
Flue Gas Temperature		°C	At exit point
Combustion Chamber Temperature		°C	Thermocouple reading
Boiler Load Condition			Full/Part load

Section 3. Air-Fuel Ratio and Efficiency Data

Field	Data / Measurement	Units	Remarks
Flue Gas Flow Rate		m ³ /hr	Measured at emission point
Flue Gas Composition: CO ₂		%	Gas analyzer
Flue Gas Composition: O ₂		%	Gas analyzer
Flue Gas Composition: CO		ppm	Gas analyzer
Flue Gas Composition: NO _x		ppm	Gas analyzer
Flue Gas Composition: SO ₂		ppm	Gas analyzer
Calculated Air-Fuel Ratio			Based on measurements
Overall Boiler Efficiency		%	Calculated

Section 4. Environmental Emission Data

Field	Data / Measurement	Units	Remarks
CO ₂ Emission Rate		kg/h	Derived from flow and concentration
CO Emission Rate		g/h	Derived from flow and ppm
NO _x Emission Rate		g/h	Derived from flow and ppm
SO ₂ Emission Rate		g/h	Derived from flow and ppm
Particulate Matter		mg/m ³	Air sampling

Section 5. Surface Heat Loss and Insulation Data

Field	Data / Measurement	Units	Remarks
Combustion Chamber Surface Temperature		°C	Thermocouple
Heat Exchange Tube Temperature		°C	Thermocouple
Insulation Surface Temperature		°C	IR thermography
Ambient Temperature		°C	Weather station
Insulation Thickness		mm	Physical measurement
Thermal Conductivity of Insulation		W/m·K	Datasheet or laboratory test
Heat Flux on Surface		W/m ²	IR thermography or heat flux sensor

Section 6. Operational and Maintenance Data

Field	Data / Measurement	Units	Remarks
Fouling Thickness on Heat Surface		mm	Visual inspection
Cleaning Schedule			e.g., Monthly
Operational Hours		hours	per shift

Section 7: Surface Temperature at Key Parts of the Boiler

Part of Boiler	Surface Temperature	Units	Method / Instrument	Notes
1. Front Surface		°C	Infrared Thermometer / Thermocouple	
2. Rear Surface		°C	Infrared Thermometer / Thermocouple	
3. Left Side Surface		°C	Infrared Thermometer / Thermocouple	
4. Right Side Surface		°C	Infrared Thermometer / Thermocouple	
5. Top Surface		°C	Infrared Thermometer / Thermocouple	
6. Door Surface		°C	Infrared Thermometer / Thermocouple	

APPENDIX IV B FLOW IN T/HR

Super heater outlet
Feed water inlet
Air flow
Economizer inlet temperature
Economizer outlet temperature
Flue gas temperature super heater panel inlet
Coal flow
Steam flow
Air flow
Feed water inlet temperature
Dry bulb temperature
Wet bulb temperature
Relative humidity
Absolute humidity kg H ₂ O/dry air
Ambient air temperature
Air heater inlet gas inlet temperature
Air heater outlet gas outlet temperature
Weight of mill rejects (kg/hr.)
Gross calorific value of mill rejects(kcal/kg)

APPENDIX IV C AIR HEATER FLUE GAS ANALYSIS

% Volume	Inlet	Outlet
CO ₂		
O ₂		
N ₂		
In economizer ash		
In fly ash		

APPENDIX IV D: Proximate Analysis

Constituents
Moisture
Ash
Volatile matter
Fixed carbon
Gross calorific value(kcal/kg)

APPENDIX IV E: Unburnt Carbon

Unburnt carbon	kg/kg of fuel
In bottom ash	0.0010

APPENDIX IV F: Ultimate Analysis

Contents	% Wt.
Carbon	
Hydrogen	
Nitrogen	
Moisture	
Ash	
Oxygen	
Sulphur	

APPENDIX IV G: DRY FLUE GAS

Quantity	Unit	Loss
Ambient air temperature(T_a)	$^{\circ}\text{C}$	
Carbon (C)	%	
Sulphur (S)	%	
Carbon dioxide at heater outlet		
Total unburnt carbon (U)	Kg/kg of fuel	
Air heater outlet gas temperature	$^{\circ}\text{C}$	
Gross calorific value Kcal/kg	Kcal/kg	
Weight of dry gas (Wd)	Kg/kg of fuel	
Sensible heat of dry gas (SH)	KJ/kg of fuel	
Dry gas loss (L_1)	%	

APPENDIX IV H: LOSS DUE TO MOISTURE IN FUEL

Quantity	Unit	Loss
Total moisture	%	
Flue gas temperature leaving air heater common outlet	°C	
Ambient air temperature	°C	
Gross calorific value	Kcal/kg	
Sensible heat of water (SW)	Kj/kg	
Loss due to moisture (L ₂)	%	

APPENDIX IV I: LOSS DUE TO HYDROGEN

Quantity	Unit	Loss
Hydrogen	%	
Loss due to hydrogen (L ₃)	%	

APPENDIX IV J: LOSS DUE TO MOISTURE IN AIR

Constituents	Unit	Loss
Absolute humidity (Ah)	Kg (H ₂ O/dry air)	
Carbon (C)	%	
Hydrogen (H)	%	
Sulphur (S)	%	
Oxygen (O ₂)	%	
Carbon dioxide (CO ₂)	%	
Nitrogen (N ₂)	%	
Air-fuel (EA)	%	
Stoichiometric air quantity (SA)	Kg/kg of fuel	
Air quantity (AQ)	Kg/kg of fuel	

S/No	Parameter Tested	Average Data
1.	Fuel firing rate	= 5500 kg/hr.
2.	Steam generation rate	= 21200 kg/hr.
3.	Steam pressure	= 40 kg/cm ² (g)
4.	Steam temperature	= 350 °C
5.	Feed water temperature	= 80 °C
6.	%CO ₂ in Flue gas	= 12
7.	%CO in flue gas	= 0.5
8.	Average flue gas temperature	= 160 °C
9.	Ambient temperature	= 27 °C
10.	Humidity in ambient air	= 0.020 kg / kg dry air
11.	Surface temperature of boiler	= 40 °C
12.	Wind velocity around the boiler	= 3.0m/s
13.	Total surface area of boiler	= 60 m ²
14.	GCV of Bottom ash	= 600 kCal/kg
15.	GCV of fly ash	= 440 kCal/kg
16.	Ratio of bottom ash to fly ash	= 70:10
Fuel Analysis (in %)		
17.	Ash content in fuel	= 7.5
18.	Moisture in wood	= 30.2
19.	Carbon content	= 38.1
20.	Hydrogen content	= 1.8
21.	Nitrogen content	= 1.4
22.	Oxygen content	= 12.48
23.	GCV of wood	= 3600 kCal/kg

APPENDIX V: SUMMARY OF HEAT BALANCE FOR COAL FIRED BOILER

Input/output Parameter	Applicable formula as per BS845:1987
Heat Input	
Losses in boiler	
1. Dry flue gas- Loss (L_1)	$L_1 = \frac{m \times c^p(T_f - T_a)}{GCV \text{ of fuel}} \times 100$
2. Loss due to hydrogen in fuel, L_2	$L_2 = \frac{9xH_2 \{584 + c^p(T_f - T_a)\}}{GCV \text{ of fuel}} \times 100$
3. Loss due to moisture in fuel, L_3	$L_3 = \frac{mx \{584 + c^p(T_f - T_a)\}}{GCV \text{ of fuel}} \times 100$
4. Loss due to moisture in air, L_4	$L_4 = \frac{\%CO \times C}{\%CO \times \%CO_2} \times \frac{5744}{GCV \text{ of fuel}} \times 100$
5. Partial combustion of C to CO, L_5	$L_5 = \frac{\%CO \times C}{\%CO \times \%CO_2} \times \frac{5744}{GCV \text{ of fuel}} \times 100$
Boiler Efficiency = 100 - (L₁ + L₂ + L₃ + L₄ + L₅) = %	

APPENDIX VI: KREJCIE AND MORGAN TABLE

<i>N</i>	<i>S</i>	<i>N</i>	<i>S</i>	<i>N</i>	<i>S</i>
10	10	220	140	1200	291
15	14	230	144	1300	297
20	19	240	148	1400	302
25	24	250	152	1500	306
30	28	260	155	1600	310
35	32	270	159	1700	313
40	36	280	162	1800	317
45	40	290	165	1900	320
50	44	300	169	2000	322
55	48	320	175	2200	327
60	52	340	181	2400	331
65	56	360	186	2600	335
70	59	380	191	2800	338
75	63	400	196	3000	341
80	66	420	201	3500	346
85	70	440	205	4000	351
90	73	460	210	4500	354
95	76	480	214	5000	357
100	80	500	217	6000	361
110	86	550	226	7000	364
120	92	600	234	8000	367
130	97	650	242	9000	368
140	103	700	248	10000	370
150	108	750	254	15000	375
160	113	800	260	20000	377
170	118	850	265	30000	379
180	123	900	269	40000	380
190	127	950	274	50000	381
200	132	1000	278	75000	382
210	136	1100	285	100000	384

Note.—*N* is population size. *S* is sample size.

Source: Krejcie & Morgan, 1970


APPENDIX VII: RESEARCH PERMIT

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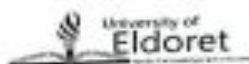
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