M. Tech

Thermal Engineering

Deepak Kumar

2023

EXPERIMENTAL INVESTIGATIONS ON THE USE OF BUTANOL, ETHANOL & DIESEL IN A COMPRESSION IGNITION ENGINE

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

THERMAL ENGINEERING

Submitted by:

DEEPAK KUMAR

(2K21/THE/06)

Under the Supervision of

Dr. RAJIV CHAUDHARY
(Professor)

&

Dr. RAGHVENDRA GAUTAM
(Assistant Professor)

MECHANICAL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road Delhi – 110042

MAY, 2023

EXPERIMENTAL INVESTIGATIONS ON THE USE OF BUTANOL, ETHANOL & DIESEL IN A COMPRESSION IGNITION ENGINE

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

THERMAL ENGINEERING

Submitted by:

DEEPAK KUMAR

(2K21/THE/06)

Under the Supervision of

Dr. RAJIV CHAUDHARY
(Professor)

&

Dr. RAGHVENDRA GAUTAM
(Assistant Professor)

MECHANICAL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road Delhi – 110042

MAY, 2023

MECHANICAL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
(Formely Delhi College of Engineering)
Bawana Road Delhi – 110042

CANDIDATE’S DECLARATION

I, **DEEPAK KUMAR**, Roll No.:- **2K21/THE/06** students of M.Tech Thermal Engineering, hereby declare that the project Dissertation titled “**EXPERIMENTAL INVESTIGATIONS ON THE USE OF BUTANOL, ETHANOL & DIESEL IN A COMPRESSION IGNITION ENGINE”** which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Date: 31.05.2023
Place: Delhi

DEEPAK KUMAR
(2K21/THE/06)

MECHANICAL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
(Formely Delhi College of Engineering)
Bawana Road Delhi – 110042

CERTIFICATE

I hereby certify that the project Dissertation titled "**EXPERIMENTAL INVESTIGATIONS ON THE USE OF BUTANOL, ETHANOL & DIESEL IN A COMPRESSION IGNITION ENGINE**" which is submitted by **DEEPAK KUMAR**, Roll No.- **2K21/THE/06** Department of Mechanical (Thermal) Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Date: 31.05.2023	**Dr. RAJIV CHAUDHARY**	**Dr. RAGHVENDRA GAUTAM**
Place: Delhi	(Professor)	(Assistant Professor)

(SUPERVISORS)

Mechanical Engineering Department
Delhi Technological University
(Formerly Delhi College of Engineering)
Bawana Road Delhi – 110042

ABSTRACT

In recent years, the growing concerns about climate change and the depletion of fossil fuel reserves have led to a significant focus on exploring alternative and sustainable fuels. One promising candidate is ethanol, a biofuel obtained from renewable sources such as corn, sugarcane, and cellulosic materials. While traditionally used as a gasoline additive, ethanol has also shown great potential as an additive or substitute for diesel fuel in compression ignition (Diesel) engines.

However, ethanol exhibits certain limitations, including its lower energy density and compatibility issues with diesel engines due to differences in physiochemical properties. To overcome these challenges, Butanol, another alcohol-based fuel, has been proposed as an additive to ethanol. Butanol possesses properties that enhance its compatibility with diesel engines, like energy density, cetane number to diesel fuel and improved lubricity.

The purpose of this study is to analyze the effects of ethanol-blended fuel on a diesel engine by examining a range of factors. In the initial phase, the researchers assessed the suitability of ethanol and diesel fuels, both with and without the incorporation of n-butanol as an additional constituent. Subsequently, a set of experimental tests were conducted to evaluate the combustion efficiency, performance, and emissions characteristics of the engine when using ethanol-diesel blends in comparison to pure diesel fuel.

The test results indicate that incorporating blends containing ethanol as a replacement for pure diesel in diesel engines is both feasible and practical. In contrast to diesel fuel, the engine operating on these blends exhibited increased peak cylinder pressure and heat release rate (HRR), also the brake thermal efficiency (BTE) is as comparable to diesel fuel. This improvement can be attributed to the higher oxygen content present in the blends, which enhances the combustion process within the engine cylinder. However, the incorporation of ethanol in the blends resulted in a rise in brake-specific fuel consumption (BSFC) attributable to the reduced calorific value of ethanol. The due to the better combustion Moreover, the study investigated the emissions properties and found that the engine operating on ethanol-diesel blends showcased reduced levels of smoke, carbon monoxide (CO), and hydrocarbon (HC) emissions in contrast to conventional diesel fuel. However, it was noticed that nitrogen oxide (NOx) emissions was higher than diesel. Through the analysis, it was determined that the optimal blend ratio of ethanol was D65E25B10, as this particular blend yielded the most favourable results in respect of combustion, performance, and emissions characteristics when in comparison to other blended fuels and pure diesel.

ACKNOWLEDGEMENTS

The present research work was carried out under the esteemed supervision of my guide Dr. Rajiv Chaudhari and Dr. Raghvendra Gautam. It is my honour and privilege to express a deep sense of gratitude to him for his panegyric efforts, ever-helping attitude, critical and valuable comments and constant inspiration. His mentorship helped me become a good researcher which I always dreamed. His words of solace and encouragement especially during difficult times shall ever be remembered by me

I am also grateful to Dr. S. K. Garg, Professor & Head, Dr. Naveen Kumar, Professor, Dr. R. C. Singh, Associate Professor and other teaching and non-teaching members of the Department of Mechanical Engineering, DTU Delhi for their help, encouragement and valuable suggestions.

I owe gratitude to the esteemed colleagues of the Centre for Advanced Studies and Research in Automotive Engineering (**CASRAE**), Delhi Technological University; for their excellent support and valuable suggestions.

I am thankful to Mr. Kamal Nain for providing all laboratory assistance. I am also thankful for Mr. Surendra Singh and Smt. Neetu Mishra, the supporting staff of CASRAE, DTU, Delhi.

Last but not least; I thank the Almighty for giving me the strength and patience to complete this work in all respects and for leading me to the path of success.

New Delhi
May, 2023

(DEEPAK KUMAR)

CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

NOMENCLATURE

@	At the rate
A/F	Air to Fuel
AC	Alternate Current
AN	Acid Number
ASTM	American Society for Testing and Materials
ATDC	After Top Dead Center
AVL-437	AVL-437 Smoke Meter
BIS	Bureau of Indian Standard
BMEP	Break Mean Effective Pressure
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
BTDC	Before Top Dead Center
^{o}C	Degree Celsius
Cc	Cubic centimeter
CFD	Computational Fluid Dynamics
CI	Compression Ignition
cm-1	Per Centimeter
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
cSt	Centi Stoke
CV	Calorific Value
D100	Neat Diesel
DI	Direct Injection
EIA	Energy Information Administration
EOI	End of Injection
ESR	Exhaust Gas Recirculation
EV	Electric Vehicle
F/A	Fuel to Air
FFV	Flexible Fuel Vehicles
FT	Fourier Transform
FTIR	Fourier Transform Infra red
G	Gram
g/cc	Gram per cubic centimeter
GHGs	Greenhouse Gases
HC	Hydrocarbon
H_2O	Water
HP	Horse Power
HRR	Heat Release Rate
Hz	Hertz
IC	Internal Combustion
ID	Indirect Injection

IR	Infra Red
IS	Indian standard
kW	Kilo Watt
kW-h	Kilo Watt Hour
NO	Nitric Oxide
Nos.	Numbers
Nox	Oxides of Nitrogen
O_2	Oxygen
PAH	Poly aromatic Hydrocarbon
PM	Particulate Matter
Ppm	Parts per million
Rpm	Revolutions Per Minute
SAE	Society of Automobile Engineering
Sfc	Specific Fuel Consumption
SO_2	Suphur Dioxide
TDC	Top Dead Center
THC	Total Hydrocarbon
UBHC	Unburnt Hydrocarbon
Vs	Versus
v/v	Volume/ Volume
P	Density
%	Percent

CHAPTER 1

INTRODUCTION

1.1. MOTIVATION

Energy plays a major role in the progress and economic advancement of any nation. With the growing global population, the demand for energy across various sectors is also increasing. Presently, the most urgent challenges faced are climate change and energy security. Finding sustainable energy sources that address environmental concerns and fluctuating energy prices has become a top priority. The increasing global energy demand and apprehensions regarding the exhaustion of fossil fuels are propelling the demand for renewable and eco-friendly energy alternatives. Additionally, diesel engines are extensively employed across industries, transportation, and agriculture because of their beneficial features, including high thermal efficiency, dependability, versatility, and cost-effectiveness. However, diesel engines are observed as major contributors to environmental pollution and the energy shortage issue. In order to address energy scarcity and adhere to emerging emission standards, alternative fuels are widely regarded as highly effective solutions. The present research aims to explore and develop local fuels derived from existing sustainable energy resources as substitutes for fossil fuels, with the goal of alleviating the climate change.

1.2. ENERGY SCENARIO OF WORLD

Despite the expansion of renewable energy, the majority of the global energy mix still relies on fossil fuels like, gas, oil, and coal. In 2019, fossil fuels accounted for about 84% of primary energy consumption globally [1]. As the global population continues to grow and economies develop, energy demand is increasing. Based on the U.S. Energy Information Administration (EIA), it is forecasted that global energy demand will experience a growth of approximately 50% from 2018 to 2050 [2]. Despite significant progress in recent years, millions of people around the world still lack access to reliable, affordable energy. This is a major barrier to economic development and social progress in many regions. Figure 1.1 illustrates the fuel utilization necessary to fulfill primary energy requirements over the previous five decades, along with the estimated demand for 2040 [3].

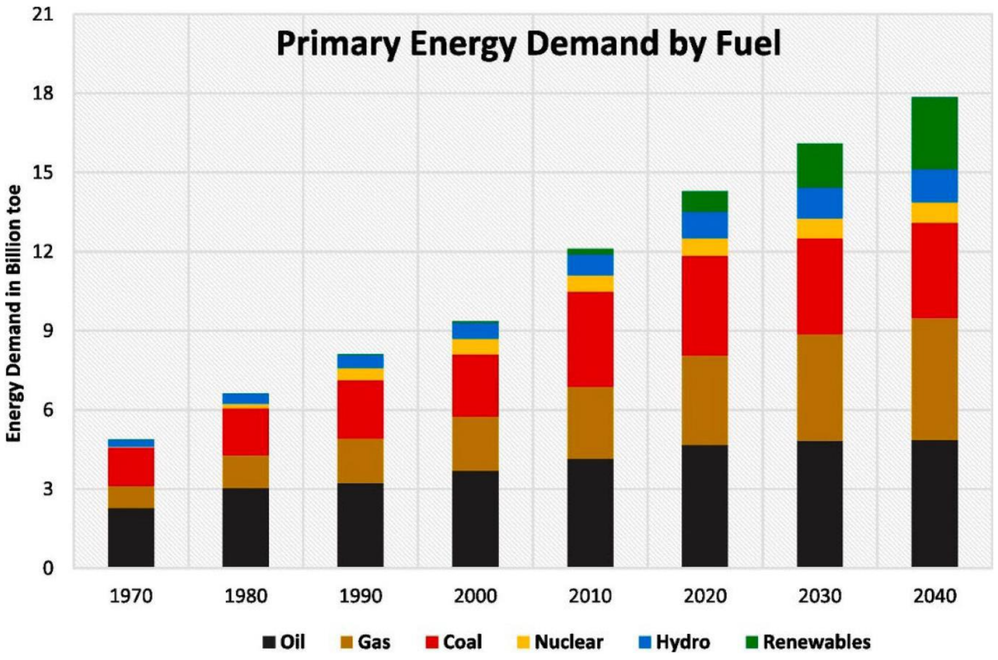

Figure 1.1: Primary energy demand by different sources

1.3. ENERGY SCENARIO OF INDIA

India, recognized as one of the world's rapidly growing economies, has been experiencing a significant surge in its energy demand. The demand for energy in India is projected to double by 2040, driven by urbanization, population growth, and industrialization [4]. Coal holds a dominant position in India's energy mix, which accounts for about 55% of the country's total energy demand [5]. Apart from coal, India's energy supply relies on other significant sources such as oil, natural gas, and hydroelectric power, as well as renewable energy sources like solar and wind power. India has set ambitious objectives to increase the share of renewable energy in its energy portfolio. However, despite the emphasis on renewable energy, fossil fuels maintain a predominant position in India's energy composition. India heavily relies on imported crude oil and ranks as the world's third-largest consumer of oil. The government has been taking steps to reduce its dependence on oil imports by promoting domestic production and exploring alternative sources of energy. India has also been focusing on improving energy efficiency to lower energy consumption and mitigate greenhouse gas emissions. The government has launched several initiatives, including the Perform, Achieve and Trade (PAT) scheme, aimed at encouraging industries to adopt energy-efficient technologies [6]. Overall, India's energy scenario is undergoing significant changes, with a shift towards renewables and cleaner sources of energy. However, there are still significant challenges to overcome, such as the high cost of renewable energy and the need for grid infrastructure improvements to enable greater integration of renewable energy sources.

1.4. DIESEL ENGINES AND THEIR ECONOMIC SIGNIFICANCE

Diesel engines have significant economic relevance in various sectors and industries. Here are some key points highlighting their importance:

1. **Transportation and Logistics:** Diesel engines are commonly used in trucks, buses, trains, ships, and other heavy-duty vehicles. Their high torque output and fuel efficiency make them well-suited for long-distance transportation and hauling heavy loads [7]. Diesel-powered vehicles are vital for the movement of goods, enabling commerce and trade, and supporting economic growth.
2. **Construction and Mining:** The construction and mining industries heavily rely on diesel engines, playing a vital role in their operations. They power heavy machinery like excavators, bulldozers, loaders, and generators. These machines require substantial power and durability, and diesel engines deliver the necessary performance and reliability in challenging working conditions.
3. **Agriculture:** Diesel engines are extensively used in agricultural machinery such as tractors, harvesters, irrigation pumps, and stationary equipment. The robustness of diesel engines makes them suitable for demanding agricultural tasks, including ploughing fields, harvesting crops, and powering irrigation systems, thereby supporting food production.
4. **Power Generation:** Diesel generators are widely used as backup power sources in commercial establishments, hospitals, data centres, and other critical facilities. They provide reliable electricity during power outages or in remote areas without access to the electric grid. Diesel generators are

also employed in off-grid locations or developing countries with inadequate infrastructure.

5. **Industrial Applications:** Various industries rely on diesel engines for their power requirements. These engines are used in manufacturing plants, construction sites, oil and gas operations, and other industrial settings. Diesel-powered machinery and equipment contribute to increased productivity and operational efficiency.

1.5. ECONOMIC IMPACT

1. **Job Creation:** The diesel engine industry, including manufacturing, maintenance, and servicing, generates employment opportunities worldwide. It supports a vast network of skilled workers, engineers, technicians, and associated service providers.
2. **Trade and Manufacturing:** Diesel engines are manufactured and traded globally, contributing to international trade and fostering economic cooperation. Many countries have thriving diesel engine manufacturing sectors, which enhance domestic industrial capabilities and exports.
3. **Fuel Efficiency:** Diesel engines are known for their fuel efficiency, delivering more mileage per gallon compared to gasoline engines. This efficiency translates into cost savings for businesses and consumers, especially in applications involving extensive fuel consumption.
4. **Reliability and Durability:** Diesel engines are renowned for their reliability, durability, and long service life. They can withstand heavy loads, operate in harsh environments, and require less maintenance compared to other engine types. This reduces downtime and maintenance costs for businesses, improving overall operational efficiency.
5. **Economic Sectors Support:** Diesel engines play a pivotal role in multiple economic sectors, ensuring the smooth functioning of transportation, agriculture, construction, and other industries. Their reliability and performance contribute to the overall productivity and growth of these sectors.

It's important to note that while diesel engines have economic advantages, there are also concerns about their environmental impact due to emissions. Efforts are being made to develop cleaner and more efficient diesel engine technologies and to transition to alternative power sources like alternative fuels in certain applications.

1.6. ENVIRONMENTAL ISSUES

Climate change: The burning of fossil fuels releases CO_2 and other GHGs gases into the atmosphere, leading to the retention of heat and the consequent rise in global temperatures. This phenomenon gives rise to various consequences, such as more frequent and intense heatwaves, droughts, floods, and storms.

Air pollution: The combustion of fossil fuels also emits pollutants like SO_2, NOx, and PM into the atmosphere. These pollutants can have detrimental effects on human health, leading to respiratory problems, heart disease, and other related health issues.

Water pollution: Fossil fuel production can also contaminate water sources through spills, leaks, and runoff, impacting aquatic ecosystems and human health.

Habitat destruction: Fossil fuel extraction and transport can disrupt ecosystems and lead to habitat destruction, particularly in sensitive areas such as forests, wetlands, and oceans.

Natural resource depletion: Fossil fuels are finite resources, and their extraction can lead to the depletion of natural resources such as oil and gas reserves, as well as other resources like water and land.

These environmental issues have significant impacts on human health, the economy, and the natural world, and they highlight the need for a transition to cleaner, renewable energy sources. The utilization of fossil fuels for energy production stands as the primary contributor to greenhouse gas emissions, which serve as the driving force behind climate change. Addressing these emissions is a major challenge for the global community. Climate change refers to a persistent alteration in the Earth's climate patterns over an extended period, marked by increasing global temperatures, shifts in precipitation patterns, rising sea levels, and more frequent occurrence of extreme weather events. The main causes of climate change are anthropogenic activities, primarily the burning of fossil fuels and deforestation. These activities not only generate air pollution but also contribute to climate change. Air pollution, arising from the utilization of fossil fuels, transportation, industrial operations, and various other human undertakings, poses significant health risks while also exacerbating climate change.

1.7. NEED FOR ALTERNATIVE FUELS

There are several reasons why there is a necessity for alternative fuels for CI engines. Here are some of the key reasons:

Environmental concerns: Diesel engines emit various pollutants, including NOx, PM, and greenhouse gases (GHGs) such as CO_2 [8]. These emissions contribute to air pollution, smog formation, and climate change. Alternative fuels can help reduce these harmful emissions and mitigate their impact on the environment.

Energy security: Diesel fuel is predominantly derived from crude oil, which is a finite resource and subject to price volatility and geopolitical tensions. Developing and utilizing alternative fuels reduces dependence on fossil fuels, diversifies energy sources, and enhances energy security.

Climate change mitigation: Diesel engines make substantial contributions to global carbon dioxide (CO_2) emissions, which serve as the primary catalyst for climate change. Alternative fuels, especially those categorized as low-carbon or carbon-neutral, have the potential to effectively decrease the carbon footprint associated with transportation and actively contribute to the global fight against climate change.

Renewable energy integration: Many alternative fuels are derived from renewable sources, such as biofuels produced from crops, algae, or waste materials. By using these fuels, diesel engines can be powered by energy sources that can be replenished, reducing reliance on non-renewable fossil fuels.

Health benefits: Emissions from the diesel engine, especially PM and NOx, have adverse effects on nature as well as human health, contributing to air pollution, respiratory problems, cardiovascular diseases, and other health issues. Alternative fuels that produce fewer harmful emissions can help improve air quality and protect public health.

Technological advancements: The development of alternative fuels often goes hand in hand with advancements in engine technologies. Adopting alternative fuels can drive innovation in diesel engine design, leading to more efficient and cleaner engines overall.

Some examples of alternative fuels for diesel engines include biodiesel, renewable diesel, synthetic fuels, hydrogen, natural gas (compressed or liquefied), and electrification through hybrid or electric powertrains. It's important to note that the viability and widespread adoption of alternative fuels depend on various factors, including availability, infrastructure, cost, energy density, and compatibility with existing engines. Ongoing research, development, and investment are crucial to realizing the full potential of alternative fuels for diesel engines.

1.8. ALTERNATIVE FUELS FOR DIESEL ENGINE

The increasing prominence of diesel engines in recent years has highlighted the urgent need for alternative fuels. The use of conventional fossil diesel fuel not only leads to environmental degradation but also contributes to the depletion of finite fossil fuel reserves. It is crucial to address this dual challenge by embracing alternative fuels that are renewable and compatible with existing engine systems, fuel infrastructure, and storage facilities. Given the significant role that diesel engines play in the Indian economy across various sectors, bio-derived fuels offer a viable solution.

Biofuels, which are derived from organic substances, provide a renewable and feasible substitute for conventional petroleum in the agriculture and transportation industries [9]. Diesel engines are now recognized worldwide as effective measures for addressing environmental degradation, ensuring energy independence, overcoming import limitations, fostering rural employment, and supporting agricultural economies. Promising biofuels like ethanol, methanol, vegetable oils, and biodiesel have emerged as highly promising alternatives, showcasing competitiveness even without the requirement of subsidies [10].

Ethanol, which serves as both a fuel and a gasoline additive, can be derived from diverse sources such as sugar, cereals, sugar beet, and molasses in Brazil, the USA, Europe, and India respectively. In Brazil, around 20% of vehicles run solely on ethanol, while the rest utilize a blend of 25% ethanol and gasoline. The USA employs a 10% ethanol-gasoline blend, Australia utilizes a 10% ethanol-gasoline blend, Sweden incorporated a 5% blend, and. In India, the use of a 25% ethanol-gasoline blend by 2025 has been approved by the government.

Methanol, although potentially derived from grain, is commonly sourced from natural gas. Although natural gas is considered to have a lesser impact on the environmental relative to other fossil fuels, the utilization of renewable fuels would offer even greater benefits. Methanol production can also be sourced from wood or coal; however, this approach presents additional challenges and lower efficiency when compared to using natural gas.

Biodiesel, which is derived from vegetable oils, is generated through a chemical process known as transesterification, utilizing both fresh and recycled vegetable oils along with animal fats [11]. Biodiesel has the capability to be blended with petroleum diesel in any ratio, and its elevated cetane number enhances combustion, even when combined with petroleum diesel. Additionally, biodiesel can be used as an additive to accomplish various goals, such as lowering sulfur content, compensating for lubricity reduction, and enhancing the CN of diesel fuel.

While most fuels generate CO_2 emissions, which in turn increases the greenhouse effect, the use of biomass energy typically results in a net reduction of CO_2 emissions than than fossil fuels. Furthermore, the emission of SO_2, a significant air pollutant, tends to be considerably lower when employing biomass energy because of the minimal sulfur concentration in plants and trees. This reduction in SO_2 emissions is accompanied by a decrease in traditional motor pollutants like carbon monoxide, unburned hydrocarbons, and particulates, although the extent of these reductions may vary. However, the use of biofuels may lead to increased emissions of nitrogen oxides and aldehydes. The choice of liquid biofuel depends on local priorities, as there is no clear advantage of one over the others.

Certain alternative fuels can be used directly, while others require processing to align their properties closely with those of conventional fuels. An encouraging liquid alternative for fuel is ethanol, which can be derived from renewable sources like grains. Ethanol offers an appealing choice for IC engines because of its renewable characteristics and the potential to decrease environmental impact [12].

1.8.1. ALCOHOLS AS AN ALTERNATIVE FUELS

The potential of alcohols like ethanol and methanol to diminish GHGs emissions and reduce reliance on fossil fuels has led to their increased recognition as alternative fuels. Here are some key points about alcohol as alternative fuel:

Ethanol: Ethanol is primarily produced from crops rich in starch or sugar, such as corn, sugarcane, and wheat. It can be mixed with gasoline or utilize as a standalone fuel in specially designed-engines. It has a higher octane rating than gasoline, which can improve engine performance and efficiency. Furthermore, it serves as a renewable fuel source capable of contributing to the reduction of CO emissions.

Methanol: Methanol, commonly referred to as wood alcohol, can be generated from diverse feedstocks such as natural gas, coal, biomass, and even carbon dioxide. Methanol is less commonly used as a transportation fuel compared to ethanol, but it has potential as a renewable fuel due to its clean-burning characteristics and lower emissions of pollutants like nitrogen oxides (NOx). Methanol can be used in certain types of vehicles, such as flexible fuel vehicles (FFVs) or those with methanol-specific engines [13].

1.8.2. ADVANTAGES OF ALCOHOLS AS ALTERNATIVE FUELS

Renewable: Renewable sources such as plants and biomass can be utilized to produce ethanol and methanol, thereby decreasing dependence on finite fossil fuel reserves.

Lower Carbon Footprint: Alcohols, especially when derived from biomass or renewable sources, can have lower carbon dioxide emissions compared to fossil fuels. This helps mitigate climate change.

Improved Combustion: Ethanol has a higher octane rating, which allows for higher compression ratios and more efficient combustion. It can enhance engine performance and reduce emissions of certain pollutants.

Domestic Production: Producing alcohol as an alternative fuel can promote domestic energy production, potentially reducing dependence on imported oil and enhancing energy security.

1.8.3. CHALLENGES AND CONSIDERATIONS

Energy Content: Alcohols have lower energy content compared to gasoline, resulting in reduced fuel efficiency and potentially increased fuel consumption.

Infrastructure: Widespread adoption of alcohols as alternative fuels would require establishing a robust distribution and refuelling infrastructure. This includes ethanol or methanol blending facilities, storage tanks, and compatible fueling stations.

Feedstock Availability: Scaling up alcohol production may compete with food production or raise concerns about deforestation or land-use change. Using non-food feedstocks and advanced conversion technologies can help address these concerns.

Vehicle Compatibility: For vehicles to operate on alcohol fuels, they either need to be designed or modified accordingly. Flexible fuel vehicles (FFVs) have the capability to run on ethanol-gasoline blends, whereas specific engine modifications or dedicated vehicles are required for the use of methanol.

It's worth noting that the suitability of alcohols as alternative fuels varies depending on factors such as regional availability of feedstocks, energy policies, infrastructure development, and vehicle technologies. Ongoing research and technological advancements are being pursued to optimize the production, distribution, and utilization of alcohol as a viable alternative to traditional fossil fuels.

1.9. BUTANOL AS SOLVENT/ADDITIVE

Butanol can indeed be used as an additive in ethanol-diesel blends to improve their performance and characteristics. Blending ethanol with diesel fuel is a common practice to reduce emissions and enhance fuel properties. Butanol, specifically n-butanol, has been studied as an alternative additive for such blends due to its favorable properties. Here are some key points regarding the use of butanol as an additive for ethanol-diesel blends:

Improved Cetane Number: Butanol has a higher cetane number than ethanol, which is a measure of the fuel's ignition quality. Adding butanol to ethanol-diesel blends can raise the cetane number, improving the combustion efficiency and reducing ignition delay.

Enhanced Lubricity: Diesel fuel possesses better lubricity compared to ethanol, and the addition of butanol can help enhance the lubricating properties of ethanol-diesel blends. This is particularly important for the proper functioning of fuel injection systems and to mitigate potential wear in engines.

Reduced Phase Separation: Ethanol-diesel blends can experience phase separation when exposed to water or in cold conditions. However, the addition of butanol can decrease the likelihood of phase separation, improving the stability and storage characteristics of the blend.

Lower Water Absorption: Ethanol has a higher affinity for water, leading to the absorption of moisture from the atmosphere. This can be problematic for ethanol-diesel blends. Butanol has lower water solubility, reducing the water absorption and potential issues related to water contamination.

Improved Energy Content: Butanol has a higher energy content compared to ethanol, making it a more energy-dense fuel. The addition of butanol to ethanol-diesel blends can increase the overall energy content, resulting in improved fuel efficiency.

The optimal blend composition and the specific effects of adding butanol can depend on various factors, including the engine type, operating conditions, and the desired fuel properties. Extensive research and testing are necessary to determine the most suitable blend ratio and to ensure compatibility with the intended application. It is also important to comply with applicable regulations and standards related to fuel blending and additive usage in your region before considering the use of butanol as an additive in ethanol-diesel blends.

1.10. ORGANIZATION OF THESIS

The thesis entitled, "**EXPERIMENTAL INVESTIGATIONS ON THE USE OF, ETHANOL & BUTANOL WITH DIESEL IN A COMPRESSION IGNITION ENGINE**" provides an overview of the application of alcohols in single-cylinder four-stroke CI engines. The thesis comprises five chapters that are organized in the following structure:

CHAPTER 1: INTRODUCTION - The research background is presented, and the study is contextualized in this chapter. It starts by presenting the research motivations and proceeds to provide an overview of the energy landscape, along with the environmental issues associated with the utilization of diesel.

CHAPTER 2: LITERATURE REVIEW- This chapter refers a thorough examination of the roles played by diesel engines and inspects the emerging sources of alcohol as a viable alternative fuel. The study examines the performance, emission, and combustion characteristics of different alcohols when utilized as alternative fuels. The chapter also summarizes the findings of an extensive literature review conducted. Furthermore, It identifies the existing research gap, presents the problem statement, and outlines the objectives of the study.

CHAPTER 3: SYSTEM DEVELOPMENT AND METHODOLOGY – In this chapter, a detailed elucidation of the methodologies employed to evaluate the physio-chemical characteristics of alternative fuels is provided. It also encompasses the description of the system devised for engine trials, with comprehensive details included. The chapter outlines the procedures entailed in calculating the HRR, mass friction burnt, and conducting comprehensive engine trials. Furthermore, the report includes information about the accuracy of measurements and the associated uncertainties.

CHAPTER 4: RESULTS AND DISCUSSION – The results of the experimental work and statistical computations are thoroughly examined and discussed in this chapter. The study presents its findings and then thoroughly analyses and interprets them, making comparisons with pertinent data documented in the literature already in existence. Tables, graphs, and figures, where appropriate, are used to portray the results clearly.

CHAPTER 5: CONCLUSION – This chapter offers a concise overview of the principal findings derived from the conducted research, drawing logical conclusions based on the facts and figures obtained throughout the study. Additionally, it provides recommendations for future studies.

Lastly, the thesis includes a comprehensive list of references, appendices, and a list of publications.

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

This chapter provides a thorough review of how diesel engines work and discusses current developments in the use of alcohol as a fuel replacement. It outlines the performance, emission, and combustion potentials of various alcohols as alternative fuel options. The chapter emphasizes the findings derived from an extensive review of relevant literature. Moreover, it identifies the research gap, defines the problem statement, and delineates the research objectives in a clear manner.

2.2. REVIEW OF ETHANOL-DIESEL BLENDS

He et al. [14], studied the impact of Ethanol with diesel fuels on a four-cylinder DI diesel engine operating at 1700 rpm. Two blend concentrations, 10% and 30% ethanol by volume, were investigated. The inclusion of ethanol in diesel fuel led to alterations in the characteristics of the blended fuels. Comparing the emissions from these ethanol-diesel blends to those of pure diesel fuel, it was observed that smoke emissions were reduced at high engine loads, with minimal effects on CO, acetaldehyde, and unburned ethanol emissions. Moreover, there were some reductions in NOx and CO_2 emissions as well. However, at low loads, the reduction in smoke emissions was marginal due to the overall leaner mixture. Nevertheless, by incorporating additives and ignition improvers, emissions of CO, unburned ethanol, acetaldehyde, and total hydrocarbons could be moderately decreased, even surpassing the emissions of pure diesel (E0) at low loads.

Wei et al. [15], studied the impacts of ESR and EGR on various performance parameters of RCCI engines with high load by using Converge CFD code at a uniform speed of 2000 rpm. The study proposed that increasing the ESR led to significant increases in in-cylinder pressure, gas temperature, and peak pressure. However, the knocking tendency increased rapidly with the increase of ESR.

Additionally, the implementation of EGR resulted in a decrease in NOx but a rise in the soot, Hydrocarbon, and CO in the cylinder.

Chen et al. [16], examined the impact of ESR on the various combustion and performance characteristics of a dual-fuel engine was examined. The study involved conducting experiments with blends of diesel and methanol, ethanol, and n-butanol. The test was performed at a consistent speed of 1600 rpm and medium load while varying the ESR from 0% to 40%. Among the alcohols tested, methanol exhibited the most significant influence on ID and combustion duration. With an increase in the ESR, the BTE improved for engines running on methanol and ethanol blends, while it reduced for the n-butanol blend. Additionally, the particle concentration in the diesel engine decreased with the incorporation of alcohol, and the nitrogen oxide emissions varied depending on the specific alcohol used and the level of ESR.

Ge et al. [17], evaluated the influence on the performance parameters and PM morphology of the CI engine. The experiment reveals that introducing ethanol to diesel fuel did not notably affect the peak pressure, but it did postpone the SOC, increase the maximum HRR, and reduce the combustion duration. Additionally, blending ethanol with diesel fuel resulted in decreased smoke emissions and NOx while reducing the particle diameter. These findings suggest that ethanol is likely to be a valuable alternative for diesel fuel, leading to enhanced engine performance and reduced emissions.

Saravanan et al. [18], devised a configuration for an EFDE integrated with EGR and conducted experiments to estimate the various performance parameters of the EFDE under various EGR scenarios. These scenarios encompassed the utilization of ethanol with a coating, ethanol with a coating and 10% EGR, and ethanol with a coating and 20% EGR. The outcomes of the study revealed that the BTE of ethanol at peak load was highest for the LHR-RT (Low Heat Rejection - Ricardo Twin Swirl) engine. However, as the EGR rates increased, the BTE decreased due to a reduction in the available air for combustion. At maximum load, the NOx emissions were increased when ethanol was used in contrast to the 10% and 20% exhaust gas recirculation (EGR) scenarios. Generally, the introduction of exhaust gas, through EGR, resulted in a reduction in heat release owing to the presence of already combusted gases in the process.

Shanmugam et al. [19], carried out a study to assess the impact of different additives, namely oleic acid, ethylene acetate and isopropanol, on the stability of ethanol blends for compression ignition The test were performed at a consistent speed of 1500 rpm. Among the additives investigated, oleic acid demonstrated the highest efficacy in achieving a uniform mixture. The experimental findings showcased enhanced performance characteristics when DEE was added to the blend, including an increase in BTE and a reduction in SEC. However, higher concentrations of ethanol in the blend resulted in increased emissions of hydrocarbon and carbon monoxide, which can be accounted for the higher LHV of ethanol.

Asad et al. [20], carried out a performance assessment of dual-fuel combustion using ethanol compared to pure diesel high-temperature combustion (HTC) using a single-cylinder diesel engine. The experimental investigation were performed at a consistent speed of 1500 rpm, covering various load conditions. The findings indicated that dual-fuel combustion demonstrated notably reduced tailpipe emissions comparison to diesel HTC. Moreover, the combustion exhibited higher gross indicated efficiency at increased loads. The research also investigated the influence of a NOx SCR system on net ITE. The findings revealed that combustion necessitated a lower SCR conversion efficiency and lower urea consumption in comparison to diesel HTC to attain comparable levels of NOx emissions. This suggests that dual-fuel combustion with ethanol can achieve desirable emissions control with more efficient use of the SCR system.

Yoon et al. [21], examined engine performance parameters with various diesel-bioethanol blends in a CRDI engine at a uniform speed and variable engine loads. The findings indicated that the inclusion of ethanol had no substantial impact on in-cylinder pressure and heat release rate. Nevertheless, the incorporation of ethanol caused lesser emissions of NOx, CO, and smoke. However, one disadvantage of utilizing ethanol was an improvement in BSFC because of its lesser Calorific value in contrast with diesel fuel.

In a research conducted by Lin et al. [22], examined the effects of fuel depth and ullage height on the liquid flame dispersion diesel fuel and 5% ethanol-diesel mixes. The study yielded several noteworthy findings. Initially, as the fuel depth increased in the presence of the ullage effect, the rate of flame dispersion demonstrated an initial rise followed by reaching a steady value. Furthermore, in the scenario of deep fuel pools, the surface velocity increased in correlation with the increase in fuel depth. These results indicate that the surface velocity of the liquid flame dispersion is influenced by the depth of the fuel. the frequency of flash flame pulsation displayed minimal sensitivity to variations in fuel depth and demonstrated a negative correlation with ullage height. This suggests that the ullage height has an impact on the frequency of flash flame pulsation. These findings hold significant implications for enhancing safety protocols, management, application, and manufacturing practices of ethanol blends in the energy merket.

In their study, Lin et al. [23], evaluated the potential impact of additives in ternary blend fuels comprising ethanol, biodiesel, and diesel. The researchers focused on utilizing ethanol derived from food waste to enhance the profitability of the blends. Two different volume ratios were considered: 9.1% ethanol, 26.2% biodiesel, and 64.7% diesel; and 4.3% ethanol, 20.2% biodiesel, and 75.5% diesel. The outcomes of the study revealed that by incorporating ethanol-biodiesel-diesel blends with zero cost for waste feedstock, there was a significant potential for profit. The researchers projected that the potential profit could reach a significant amount of $13.42 million. This economic assessment highlights the viability and economic benefits of utilizing ethanol derived from food waste as an additive in ternary blend fuels. The findings demonstrate the potential for generating substantial profits while utilizing sustainable and renewable fuel sources.

Sen et al. [24], examined the implications of incorporating alcohol into diesel on operation ignition, and effluent emissions. The researchers used alcohol blends, specifically B10 (10% alcohol), E10 (10% ethanol), and M10 (10% methanol), mixed with diesel. The result shows that blends exhibited longer ignition delays. Moreover, the alcohol blends led to increased peak cylinder pressures and higher maximum HRR in contrast to diesel. However, pure diesel fuel exhibited the lower fuel expenditure and the higher thermal efficiency among the tested fuels. These results imply that adding alcohol to diesel fuel did not boost the engine's fuel economy. Regarding exhaust emissions, the introduction of alcohol in the fuel blend resulted in a slight elevation in NOx emissions. However, the utilization of alcohol blends led to decreased levels of smoke and CO emissions when compared to pure diesel fuel. This implies that the adoption of alcohol blends has the potential to contribute to the reduction of PM and CO emissions from engines.

In their study, Lee et al. [25], focused on investigating the influence of the energy fraction of ethanol in dual-fuel operation with diesel on combustion and emission parameters under various load. The experiments were performed on an engine operating at a consistent speed of 1000 rpm, with the ethanol fraction in the blend being systematically varied from zero to approximately 50%. The study's results unveiled significant findings concerning the impact of the ethanol concentration on combustion and emissions. As the ethanol fraction in the fuel blend increased, there was a corresponding reduction in emissions of NOx and PM. This suggests that incorporating ethanol into diesel fuel can be beneficial in mitigating these detrimental emissions.

Taghizadeh-Alisaraei and Rezaei-Asl [26], conducted a study to examine the impacts of ethanol with regular diesel fuel on engine performance, combustion characteristics, knocking, and vibration. The test were conducted using a 4-stroke, six-cylinder diesel engine operating under full load conditions, with rotational speeds varying between 1600 and 2000 rpm. Ethanol was blended with diesel in fraction ranging from 2% to 12% by volume, resulting in a total of seven distinct fuel blends. Findings indicated that when the ethanol content exceeded 8%, it caused a prolonged ID and irregular operation of the engine. These effects led to increased cylinder pressure and eventually resulted in engine knocking.

In a study conducted by Sayin et al. [27], examined the impact of binary fuel blends, specifically ethanol and methanol combined with diesel, on engine performance and emissions. These experiments were conducted using a DI diesel engine. The experiments were conducted at two distinct engine speeds, while keeping the engine load constant. The study's results revealed that the introduction of ethanol into diesel fuel resulted in a decrease in BTE, smoke opacity, CO emissions, and UHC emissions. However, the inclusion of ethanol in diesel fuel led to increased NOx emissions and BSFC. Methanol blended with diesel fuel also produced similar effects. Moreover, both ethanol and methanol blended fuels exhibited higher EGT when compared to pure diesel fuel. These findings suggest that while blending ethanol and methanol can result in reductions in certain emissions such as CO and smoke opacity, there are drawbacks like higher NOx emissions and elevated fuel consumption.

In their experimental study, Hansdah et al. [28], conducted research to examine the impacts of bioethanol fumigation on engine performance parameters. The study focused on a fully loaded, air-cooled, DI diesel engine with a single cylinder. The bioethanol utilized in the study was obtained through the fermentation process of maduca indica flowers. The researchers introduced this bioethanol into the engine at four distinct flow rates: 0.24, 0.48, 0.96, and 1.22 kg/h. The outcomes of the study indicated that bioethanol fumigation led to a reduction in smoke emissions and brake-specific NOx emissions. This suggests that the use of bioethanol as a fumigant can help mitigate the environmental impact of diesel engine combustion. However, the fumigation process also resulted in a prolonged ID of approximately 2-3 degrees Celsius crank angle (°CA), which may have implications for engine performance and efficiency. Additionally, the study found that the peak CP and HRR values elevated with higher amounts of bioethanol injected into the engine. The study findings revealed that the highest values of CP and HRR were observed when the bioethanol fumigation rate reached 1.22 kg/h. This indicates that higher flow rates of bioethanol can result in more intense combustion.

Ren et al. [29], studied the impact of incorporating various oxygenate additives into diesel fuel on engine combustion and emissions in a direct-injection diesel engine. The study employed diesel as the base fuel and evaluated various oxygenate additives, including ethanol, diethyl carbonate, dimethoxymethane, diethyl adipate, dimethyl carbonate, and diglyme. The results indicated that increasing the mass fraction of oxygen in the blends, irrespective of the specific oxygenate additive employed, led to a decrease in the concentration of smoke emissions. This suggests that the inclusion of oxygenate additives in diesel fuel can contribute to improved combustion efficiency, reduced thermal efficiency and particulate emissions. However, the study did not observe significant changes in nitrogen oxide (NOx) emissions or exhaust gas temperatures with the application of diesel-oxygenate blends.

Abu-Qudais et al. [30], conducted research to examine the impact of ethanol-diesel fuel on engine performance and exhaust gas emissions. The experiments were performed using a single-cylinder diesel engine. They explored two different approaches for incorporating ethanol into the fuel: fumigation and blending. For fumigation, the researchers determined that an optimal ethanol concentration of 20% by volume resulted in significant improvements in engine performance. This concentration led to a 7.5% increase in brake thermal efficiency, indicating better utilization of the fuel's energy, and a substantial 51% reduction in soot mass concentration, indicating reduced particulate emissions. However, there were also drawbacks associated with this approach, as the fumigation of ethanol leds to an increase 55% in CO and 36% in hydrocarbon emissions. In the case of the blending method, the researchers found that an optimal ethanol percentage of 15% in the ethanol-diesel blend yielded positive results. This blend led to a 3.6% improvement in BTE and a 32% reduction in soot mass concentration, indicating improved combustion and reduced particulate emissions. However, similar to the fumigation approach, there were trade-offs in terms of emissions. Incorporating ethanol into the fuel blend resulted in a significant rise of 43.3% in CO emissions and 34% in HC emissions.

Putrasari et al. [31], examined the effects of ethanol blends on DI, two-cylinder diesel engines. They varied the engine loads from 0 to 60 Nm and tested different concentrations of ethanol, including 2.5%, 5%, 7.5%, and 10%. As the ethanol percentages increased, there was a noticeable enhancement in engine power and IMEP, suggesting improved combustion efficiency and power output. Regarding emissions, the research discovered that higher concentrations of ethanol in the fuel blend resulted in decreases in hydrocarbon (HC), smoke, and carbon monoxide (CO) emissions. Additionally, as the ethanol fraction increased, the lubricating oil temperature exhibited an increase, which could have potential implications for engine durability and performance. Furthermore, the study found that higher ethanol concentrations in the blend resulted in decreased exhaust gas temperatures.

Júnior and Martins [32], conducted a study to examine the effects of port injection of ethanol using CI engine operating in dual-fuel mode. Diesel fuel was used for direct injection, when injecting ethanol into the intake port. The experiments were carried out at various compression ratios. The study observed a substantial decrease of approximately 60% in NOx emissions when ethanol was utilized as a port injection fuel, in comparison to using pure diesel fuel. Additionally, it led to a reduce in exhaust gas temperature. Furthermore, peak combustion pressure increased when using ethanol-diesel blends. These findings indicate that incorporating ethanol through the port injection can have a positive impact on reducing NOx emissions and enhancing the combustion characteristics of diesel engines.

Jamrozik et al. [33], conducted research to assess the impact of blending different alcohols with diesel fuel at different energy ratios in a CI engine. The experimental findings revealed that the incorporation of methanol or ethanol into diesel fuel led to enhanced thermal efficiency when compared to the use of pure diesel fuel. Nevertheless, the inclusion of alcohol in the fuel blend led to elevated emissions of NOx, CO, and CO_2, although the emissions of HC remained relatively unchanged. Furthermore, the peak values of CP, HRR, and EGT were higher with the introduction of alcohol into the blend, particularly up to an alcohol proportion of 55%. Beyond this proportion, these values started to decrease instead of further increase.

Sahu et al. [34], aimed to examine the combustion stability and emission characteristics of ethanol-diesel blends in a CRDI diesel engine. The blends consisted of 5% (E05) and 10% (E10) volume/volume ethanol, along with diesel fuel (D100), under different load conditions. The results indicated that the incorporation of ethanol enhanced combustion stability, as demonstrated by reduced standard deviations in the combustion process. Specifically, E10 exhibited the most stable combustion compared to D100 and E05 under the tested load conditions (40 Nm). Furthermore, the inclusion of ethanol in the blends resulted in a decreased carbon-to-hydrogen ratio, resulting in reduced emissions of CO, HC, and smoke in the exhaust gases. The emissions were further reduced with higher proportions of ethanol in the blends compared to the base fuel. These findings underscore the potential of ethanol-diesel blends to improve combustion stability and mitigate emissions in diesel engines.

In a study by Rosa et al. [35], the exergy performance of a dual-fuel engine utilizing diesel and ethanol fuels was examined. The experiments were conducted on a single-cylinder engine at full load and 3000 rpm, with different ethanol energy ratios ranging from 12.4% to 50.7%. The results showed that the implementation of dual-fuel combustion with diesel and ethanol led to decreased exergy losses compared to traditional diesel combustion. Additionally, a rise in the ethanol energy ratio was linked to an enhancement in second-law efficiency. The study demonstrated a maximum exergy efficiency of 33.4% when employing an ethanol energy ratio of 12.4%. Moreover, it was observed that both exergy destruction and entropy production decreased with enhance in the ethanol energy ratio. These outcomes emphasize the potential of ethanol in dual-fuel combustion to improve the exergy performance of engines.

Pedrozo et al. [36], examined the efficacy of a lean-burn ethanol-diesel dual-fuel combustion strategy in enhancing the efficiency and emissions of a conventional diesel engine. The engine was operated at a consistent speed of 1200 rpm, with various steady-state loads spanning from 0.3 to 2.4 MPa net IMEP. The utilization of the dual-fuel combustion strategy in the engine resulted in a significant reduction of well-to-wheels greenhouse gas emissions by up to 57%, highlighting a substantial decrease in environmental impact. Additionally, the dual-fuel approach exhibited higher net ITE compared to the diesel mode across the tested IMEP range of 0.6 to 2.4 MPa, with a maximum efficiency of 47.2% achieved at 1.2 MPa IMEP. Moreover, the investigation demonstrated that incorporating ethanol in the dual-fuel combustion strategy led to a notable reduction in nitrogen oxide emissions compared to conventional diesel operations.

In their research, Giramondi et al. [37], investigated the effects of a dual-fuel injection strategy on ethanol ignition, combustion characteristics, engine performance, and nitrogen oxide emissions. At lower engine loads, the researchers noticed that reducing the time gap between ethanol and diesel injections led to higher emissions of HC and CO, which in turn resulted in lower combustion efficiencies. Conversely, at higher engine loads, enhancing the degree of premixing of ethanol resulted in increased levels of nitrogen oxide emissions. In conclusion, the study found that maintaining stable mixing-controlled combustion of ethanol could be accomplished by utilizing minimal amounts of diesel pilot injection throughout a broad range of engine loads.

2.3. ETHANOL -DIESEL BLENDS WITH ADDITIVES

Vargün et al. [38], investigated the impact on the various engine-related properties of ethanol-butanol-diesel blends using a CRDI at a uniform speed of 1600 rpm and at half load. The experiment indicated that the application of a 10% pilot injection using FBDF resulted in the highest peak pressure. Additionally, blended fuels decrease the CO and CO2 but increase NOx at the exhaust. In addition, E15B3 with a 5% pilot injection resulted in an increase in HRR when compared to FBDF.

Huang et al. [39], examined the feasibility of utilizing ethanol-diesel blends in a diesel engine. The researchers specifically focused on studying the solubility of these blends, both with and without the addition of n-butanol as an additive. The results showed that when blending 10%, 20%, 25%, and 30% ethanol with diesel, phase separation into two layers occurred. However, the introduction of a 5% butanol additive effectively prevented this phase separation phenomenon. Subsequent experimental tests were performed to assess the engine performance and emissions when utilizing the ethanol-diesel blends. The findings demonstrated the BTE of the blends were found to be on par with those of pure diesel; however, there was a slight increase in SFEC attributed to the lower CV of ethanol. The blends exhibited lower smoke emissions compared to pure diesel, whereas CO emissions decreased at half loads and increased with the utilization of the blends. However, there was a rise in hydrocarbon emissions, except at top loads and high speeds.

Nilaphai et al. [40], conducted the application of ABE blended with diesel at a uniform speed of 1400 rpm under a steady-state environment at different loads on combustion characteristics and thermal efficiency in engines. The study revealed that ABE20 had slightly lower thermal efficiency than diesel fuel, but had comparable energy consumption. The ID was increased, and the shorter duration of diffusion combustion. Moreover, the cylinder pressure and HRR during the power stroke exhibited a dissimilar specific heat ratio throughout the combustion.

Theinnoi et al. [41], carried out research investigating the effects of fuel additives in diesel-ethanol blends. Four additives, namely palm diesel, n-butanol, ethyl acetate, and di-tert-butyl peroxide (DTBP), were tested in the study. The blends were composed of 80% conventional diesel fuel, 15% ethanol fuel, and 5% of the corresponding additive. The results showed that all additives improved the stability of the blends, preventing phase separation at room temperature. DTBP exhibited the highest BTE and lower exhaust gas emissions, including CO, NOx, and soot, compared to other additives and diesel fuel. However, the blend with DTBP also had a slightly higher BSFC (>4%) compared to conventional diesel. Despite this, it remained within an acceptable range. This indicates its potential as a viable alternative fuel for CI engines in the future.

Zhu et al. [42], conducted with a CRDI engine to examine how the blend of n-butanol with diesel affects particulate matter (PM) emissions by fuelling different fuel blends. According to the findings, incorporating n-butanol improved the fuel and oxidizer mixing process, leading to a decreased mean cylinder temperature, lowered NOx emissions, and reduced PM emissions. In addition, the investigation utilized Raman spectroscopy to examine the soot particles in the emissions. The results indicated that additives enhanced the oxidation capability of the soot particles, whereas a reduced combustion period resulted in the increased disorder of the particles.

Atelge et al. [43], investigated combustion, emission, and exergy analyses of the Diesel-Ethanol-Butanol (D80E10B10) fuel blend under various circumstances and at a uniform speed of 1750 rpm. The outcomes demonstrated that the ternary blend fuel commonly raised BSFC and lowered BTE in comparison to diesel fuel. D80E10B10 resulted in a 7.2% increment in BSFC and a 1.3% decrement in BTE relative to diesel, specifically, at maximum load. However, D80E10B10 exhibited superior performance of CO, hydrocarbon, and NOx emissions with respect to diesel.

El-Seesy et al. [44], evaluated the implication of n-butanol as an additive for ethanol/Jatropha biodiesel blends in engines, focusing on stability, combustion, and emission parameters under various loading conditions and constant speeds. According to the findings, phase separation did not occur for more than two months under typical conditions. Adding ethanol in diesel improves the pmax and HRR, as well as longer the ID, resulting lower in BSFC compared to Jatropha methyl ester fuel. Additionally, it decreases the CO, UHCs, and NOx by 40% each. The combination of ethanol with n-butanol and JME as an additive may have the ability to enhance the utilization of renewable energy in engines.

Ahmad et al. [45]examined the impacts on the performance parameters of butanol as an additive in diesel, mango seed biodiesel (MSB) using a diesel engine. The study found that MSB20B5 blend outperformed the other blends and lowered the BSFC by 25.79% and increased BTE by 8.46% at maximum loading. Based on the study's results, the MSB20B5 ternary blend is recommended for the application in CI engines as it shows improved performance parameters and minimized the emissions of HC, NOx, CO2, and CO relative to MSB20B0 blend at full load.

2.4. PHYSICO-CHEMICAL PROPERTIES BETWEEN DIESEL AND ETHANOL FUEL

Diesel and ethanol are two separate types of fuels characterized by their unique physical and chemical characteristics. Diesel fuel is derived from crude oil and primarily consists of hydrocarbon compounds, such as alkanes and aromatic hydrocarbons. In contrast, ethanol fuel, also known as bioethanol, is an alcohol-based fuel produced through the fermentation and distillation of plant materials. Table 2.1 below illustrates the distinct characteristics of diesel, ethanol, and butanol.

Table 2.1: Properties of different fuels [46]

Properties	**Diesel**	**Ethanol**	***n*-Butanol**
Mol. Formula	$C_{12}H_{26}$-$C_{14}H_{30}$	C_2H_5-OH	C_4H_9-OH
Mol. Weight (kg/kmol)	191–210	45.88	75.12
Density (kg/m^3) at 15℃	838	790.2	810.1
Flashpoint (℃)	72	14.5	27
Boiling point (℃)	181–358	79.3	116.2
Cetane number	51.5	8.2	16
LHE (kJ/kg)	252–288	919.37	582.24
water solubility at 20℃(%weight)	Immiscible	Miscible	8.1
C(%weight)	85.83	51.84	65.22
O(%weight)	0.0	35.23	22.15
H(%weight)	14.20	12.92	13.54
C/H ratio	5.98	3.92	5.02
Self-ignition temperature (ºC)	248–302	363	343
LHV (MJ/Kg)	44.15	27.08	34.17
Vapour pressure (mmHg)	0.42	54.6	6.8
Saturation pressure (kPa) at 38℃	2.08	14.06	2.94
Lubricity (µm corrected wear scar)	314.8	1056.5	592.10
Kinematic Viscosity at 40℃(mm/s^2)	3.45	0.98	2.56

In terms of energy content, diesel fuel has a higher energy content per unit volume in comparison to ethanol. Diesel typically has a lower octane rating, indicating its resistance to knocking or detonation in spark-ignition engines. On the flip side, ethanol boasts a higher octane rating, rendering it appropriate for high-compression engines. In terms of density, diesel fuel outweighs ethanol. Diesel fuel finds extensive application in compression-ignition engines, where it is sparked by the heat generated from air compression. When considering environmental consequences, the combustion of diesel fuel results in elevated emissions of CO_2 particulate matter, and nitrogen oxides, contributing to air pollution and the greenhouse effect. Conversely, ethanol combustion generates fewer greenhouse gas emissions compared to diesel, and it is considered a renewable fuel source because it can be generated from biomass, reducing reliance on fossil fuels.

It should be emphasized that the particular characteristics discussed earlier may vary depending on the formulation, additives, and fuel blends employed for diesel and ethanol.

2.5. OUTCOMES OF LITERATURE REVIEW

After conducting a comprehensive review of the literature, the following key findings have been summarized:

- ➢ Diesel engines are crucial to the operation of countless vehicles used on roads and off roads, serving as a vital component supporting worldwide economic growth.
- ➢ Ethanol is promising as diesel engine fuel, which can be utilised in four different ways like
    - Alcohol-Diesel fuel emulsions
    - Dual injection
    - Fumigation
    - Alcohol-Diesel fuel blends
- ➢ Ethanol can be blended with diesel fuel up to 45% without requiring any modifications to the existing engine.
- ➢ The introduction of ethanol into diesel fuel alters the properties of the fuel blends, including density, CN, viscosity, calorific value, and distillation

temperatures. These modifications have implications for the combustion process, engine performance, and emissions.

- As the proportion of ethanol in the fuel blend increased, there was a corresponding increase in engine power and IMEP. Additionally, this increase in ethanol content resulted in reduced emissions of HC, smoke, and CO. However, this increase in ethanol concentration also resulted in higher BSFC and an elevation in lubricating oil temperature. Furthermore, the presence of ethanol in the blend contributed to a decrease in exhaust gas temperatures.
- Once the ethanol volume in the fuel exceeded 8%, it caused a delay in ignition and irregular engine operation, leading to increased cylinder pressure and resulting in knocking phenomena in the CI engine.
- Ethanol-diesel blends were found to separate into two layers, but the addition of additives or solvents like butanol prevented or prolonged the phase separation.
- As the rates of exhaust gas recirculation (EGR) increased, the BTE experienced a decline. This decline can be attributed to the decreased availability of air for combustion. However, the increase in EGR rates resulted in a reduction in nitrogen oxide emissions. This decrease in EGT can be primarily attributed to the implementation of EGR, which leads to lower oxygen concentration and flame temperatures.

2.6. RESEARCH GAP ANALYSIS

Based on a comprehensive literature review, the following areas requiring further research were identified:

- Numerous investigations have examined various strategies, such as alcohol-diesel fuel emulsions, dual injection, and fumigation. However, the application of alcohol-diesel fuel blends has been limited in research due to the challenges associated with phase separation.
- There has been a scarcity of research conducted on the utilization of butanol as a solvent for ethanol-diesel blends.
- Less quantum of work has been done on ternary blends of diesel.

- There is a limitation of research investigating the performance and emissions of ternary blends comprising alcohol and diesel.

2.7. OBJECTIVES

The present study aims to accomplish the following research objectives:

- Preparation of fuel samples by mixing ethanol and butanol with diesel to desired extents.
- To assess the different fuel blends, their physicochemical properties will be measured in accordance with relevant international standards such as ASTM.
- To evaluate the effects of butanol on the long-term stability of ethanol-diesel fuels.
- To design a suitable experimental setup for conducting engine trials will be one of the research objectives
- The objective of this experiment is to conduct comprehensive tests on a Single Cylinder Diesel Engine using diesel fuel as a reference to establish fundamental data for future experiments.
- Additionally, the objective is to replicate these tests using ethanol-butanol-diesel blend fuels under similar conditions. This will facilitate a comprehensive analysis of combustion, performance, and emission characteristics to assess the influence of blended fuels.

CHAPTER 3

SYSTEM DEVELOPMENT AND METHODOLOGY

3.1. INTRODUCTION

In this section, a thorough explanation of the conducted experiment and the methodologies employed to achieve the objectives outlined in the preceding chapter is presented. The research methodology used in this study is summarized in Figure 3.1, providing an overview of the research process.

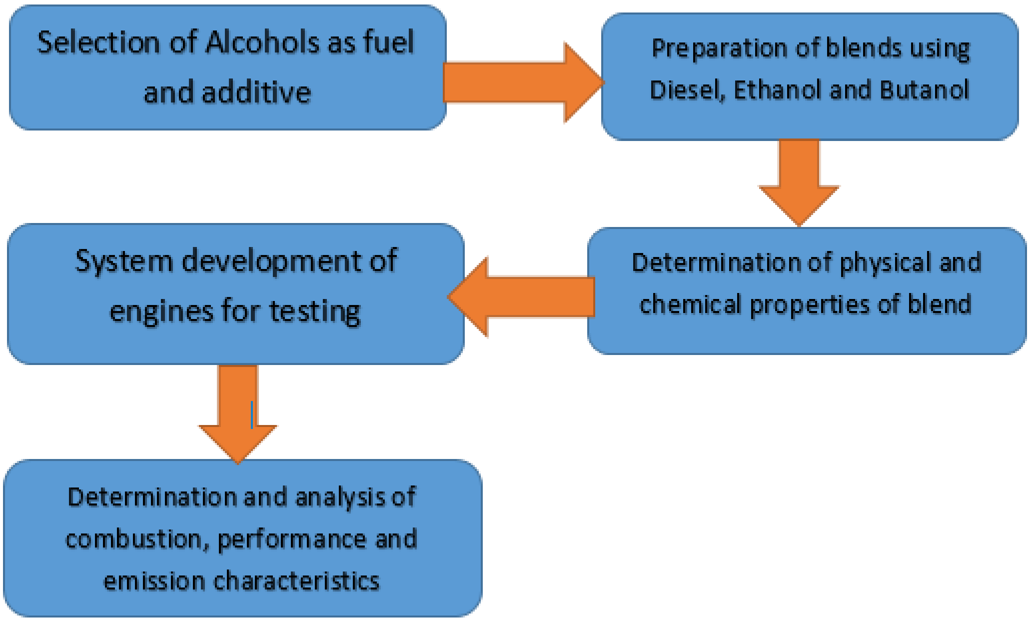

Figure 3.1: Flow chart of research methodology

In this study, the choice of potential fuels was made based on the findings documented in the existing literature on diesel-ethanol blends. This chapter describes the systematic approach used to choose solvents and prepare the test fuels necessary to perform the experimental work. The discussion encompasses the evaluation of the long-term stability of the prepared blend fuels in various environmental conditions. Additionally, relevant ASTM standards were applied to determine the fuel properties of the prepared test fuels. This chapter presents a comprehensive description of the development of the engine test rig, which was utilised to calculate the engine characteristics of the prepared fuels. The procedures and instruments employed to calculate combustion, performance, and emission parameters are also outlined in detail.

3.2. ETHANOL

Ethanol, chemically called ethyl alcohol or C_2H_5OH is a clear, colourless liquid with a slightly sweet odour. It is produced through the process of fermentation, wherein sugars or carbohydrates from diverse sources such as grains, fruits, or vegetables are enzymatically or microbially broken down by yeast or bacteria into ethanol and carbon dioxide [47]. Bioethanol also referred to as biofuel ethanol, is a renewable type of ethanol that is derived from biomass sources such as crops, agricultural residues, and cellulosic materials. Bioethanol is considered a form of biofuel, which is an environmentally friendly energy source obtained from biological materials. Commonly used as a substitute for fossil fuel or utilized as a fuel additive or standalone fuel in transportation. The production process of bioethanol is similar to traditional ethanol, involving the fermentation of carbohydrates in biomass by yeast or bacteria. Bioethanol, a renewable fuel, generated from diverse biomass sources such as sugarcane, corn, wheat, agricultural residues, forest residues, and dedicated energy crops like switchgrass [48]. It is widely acknowledged for its environmental benefits and cleaner combustion characteristics in comparison to fossil fuels. The application of bioethanol as a fuel has the potential to mitigate GHGs emissions and decrease air pollutants, contributing to a sustainable and clean energy alternative.

3.3. BUTANOL AS ADDITIVE

Butanol, also referred to as n-butanol or normal butanol, is an alcohol compound represented by the chemical formula C_4H_9OH. It occurs in four isomeric configurations: n-butanol, isobutanol, tert-butanol, and sec-butanol. Among these isomers, n-butanol is the predominant form employed in diverse industrial sectors due to its widespread applicability. It is a colourless liquid with a relatively high boiling point, making it less volatile compared to other alcohols like ethanol or methanol, and has a mild, sweet odour. Butanol is miscible with many organic solvents but has limited solubility in water.

The primary method of producing butanol is through the fermentation of biomass, similar to ethanol, where sugars or carbohydrates from feedstocks such as starch, cellulose, or lignocellulose are converted into butanol by microorganisms like bacteria or yeast. Butanol can also be produced through chemical synthesis, typically via the oxo process or through the hydrogenation of butyraldehyde [49].

Butanol has a large range of industrial applications, including its use as a solvent, a chemical intermediate in the production of plastics, resins, coatings, and other chemicals, as a component in printing inks, and as a fuel additive. It is also being researched as a potential biofuel due to its higher energy content than ethanol and its ability to be blended with gasoline without significant modifications to existing engines or fuel distribution systems. Furthermore, butanol is considered a more sustainable alternative to ethanol as it has lower hygroscopicity, and higher energy density, and can be generated from a wider range of biomass feedstocks.

Bio-butanol has potential applications as a biofuel in transportation, as a chemical intermediate in the generation of plastics, resins, and other chemicals, as a solvent, and in other industrial processes. However, there are still challenges to overcome in terms of cost, scalability, and commercial viability of bio-butanol production processes, as well as regulatory and infrastructure considerations for its widespread adoption. Ongoing research and development efforts are focused on improving the efficiency and economics of bio-butanol production, and it is considered a promising renewable energy option with potential environmental and economic benefits.

3.4. PREPARATION OF FUEL SAMPLE TEST BLENDS

Ethanol and butanol obtained from Agarwal Chemical Store in Delhi were combined with diesel in different ratios for this study. The research considered blends of 10%, 15%, 20%, 25%, and 30% ethanol in diesel, with a consistent 10% blend of butanol in each sample. The test fuel samples were formulated using volumetric measurements. For instance, to create a 10% ethanol blend and 10% butanol blend in diesel, 10ml of ethanol and 10ml of butanol were added to 80ml of diesel in a total volume of one litre. Similar procedures were followed for the other blends. The fuel samples that were prepared are displayed in Plate 3.1, and the specific names and compositions of the various test fuels can be found in Table 3.4. To ensure a consistent blend, the mixing procedure involved both intense stirring and high-speed agitation utilizing a handheld blender. Over a period of 60 days, the samples were closely monitored to assess their uniformity and the potential occurrence of phase separation. However, no signs of separation were detected, confirming the homogeneity of the mixture.

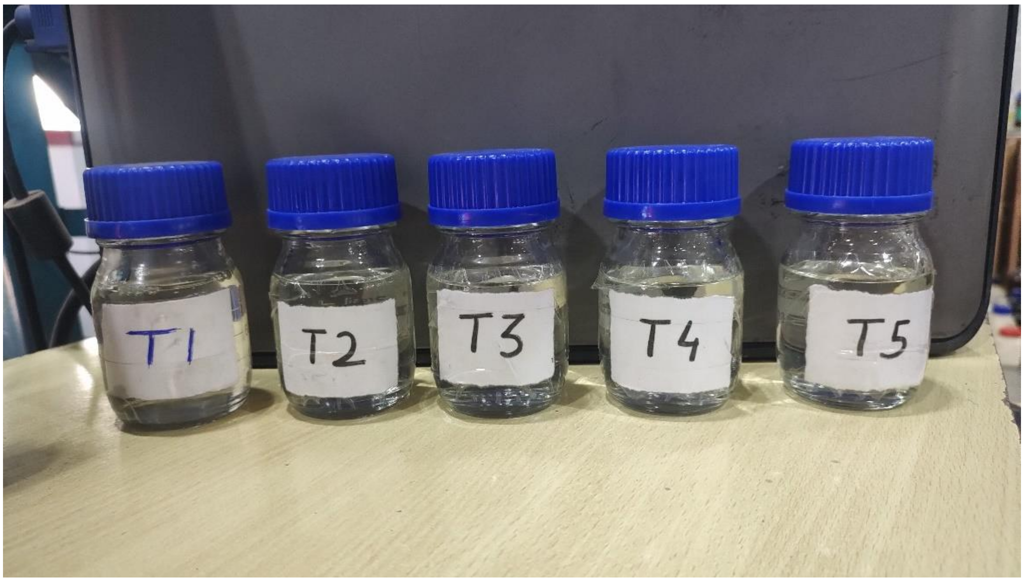

Plate 3.1: Various Fuel Samples

Table 3.1 Composition of various test fuels and it's nomenclature

Sr. No.	Test fuel composition	Nomenclature
1.	100 % Diesel	D100
2.	80 % Diesel, 10 % Ethanol, 10 % Butanol	D80E10B10 (T1)
3.	75 % Diesel, 15 % Ethanol, 10 % Butanol	D75E15B10 (T2)
4.	70 % Diesel, 20 % Ethanol, 10 % Butanol	D70E20B10 (T3)
5.	65 % Diesel, 25 % Ethanol, 10 % Butanol	D65E25B10 (T4)
6.	60 % Diesel, 30 % Ethanol, 10 % Butanol	D60E30B10 (T5)

3.5. TEST METHODS FOR DETERMINATION OF PHYSICOCHEMICAL PROPERTIES

The characterstics of the fuel and the operational parameters of the engine play a vital role in influencing the engine's performance, combustion behaviour, and emissions from the exhaust. The test fuels in this study are a mixture of diesel, ethanol, and butanol, a solvent. Consequently, the aromatic content in diesel, oxygen composition in ethanol and butanol, and the solvent properties of butanol, including its dosage, will have a notable impact on the fuel properties. Therefore, before conducting the experiments, it is essential to thoroughly analyze and compare the physio-chemical characteristics of the experimental fuels with those of diesel as a reference fuel. The following sections of the research present a detailed description of the methodologies, techniques, and apparatus utilized to evaluate the fuel properties. To facilitate this analysis, a volume of 500 ml was prepared for each test sample, enabling the assessment of both the physio-chemical attributes of the fuel. The following sub-sections provide an in-depth explanation of the various fuel properties and the corresponding testing procedures employed.

3.5.1. Density

The DMA 4500 model of an Anton Paar density metre was used to calculate the densities of the experimental fuels. The equipment utilized for these measurements is depicted in Plate 3.2. The instrument follows the ASTM D-4052 standard for measuring the specific gravity of the test fuels. The temperature for specific gravity measurements was set at a constant value of 15°C. To prepare the test fuel line, it underwent a flushing process using toluene. In a specific procedure, the sample injection port was utilized to introduce 10 ml of toluene, followed by the indroduction of 10 ml of the test sample using the same port. To ensure consistency and accuracy, the same sample was measured three times, and the obtained readings were deemed satisfactory. The final number was then calculated by averaging the three values.

Plate 3.2: Instrument used to determine the density

3.5.2. Kinematic Viscosity

For measuring the kinematic viscosity of the test samples, a Petrotest viscometer, as depicted in Plate 3.3, was employed. The viscosity evalution was conducted at a temperature of 40°C, following the guidelines of the ASTM D 445 standard. The process of measurement consisted of filling a narrow tube, known as a capillary tube, with the sample being tested. This tube had marked points indicating the lower and upper levels. The time it took for the gasoline to go from the higher to lower mark was measured using a stopwatch. By multiplying this recorded time in seconds by a constant specific to the capillary tube, the kinematic viscosity of the sample was determined using the precise formula as shown in Equation (3.1).

$$\nu = k \times t \tag{3.1}$$

Where,

ν is the kinematic viscosity in mm^2/s.

k = $0.005675 mm^2/s^2$,

t is in seconds and

Plate 3.3 Instrument used to determine the kinematic viscosity

3.5.3. Calorific Value (CV)

The determination of the CV of a liquid fuel involves the use of an isothermal bomb calorimeter, which measures the heat released when a designated amount of fuel undergoes combustion in the presence of oxygen. The CV serves as an indication of the heat generated during this combustion process. For this study, a “Parr 6100 oxygen bomb calorimeter”, as depicted in Plate 3.4, was employed. The calorimeter follows the guidelines outlined in the ASTM D-240 standard for its operation. The procedure involves filling a crucible with an exact amount of fuel and placing it between the electrodes. A nichrome wire is placed between the electrode ends and submerged in fuel to form an electrical circuit. The bomb is then carefully filled with oxygen before the fuel and electrodes are sealed inside. Afterwards, the bomb is submerged in a water-filled container, and the entire setup is placed inside the calorimeter. The calorimeter carries out the required calculations to determine the CV of the fuel based on the given setup.

Plate 3.4 Instrument to determine the calorific value

3.6. EXPERIMENTAL SET-UP

As mentioned earlier, the main objective of this present experimental study is to assess the viability of utilizing alcohol as an environmentally friendly fuel for diesel engines. Hence, the first phase entails the careful selection of appropriate diesel engines, followed by a comprehensive series of trials to study the performance, combustion, and emission attributes across different operational scenarios. The goal is to evaluate alcohol's suitability as a viable alternative fuel for engines powered by diesel fuel.

3.6.1. Selection of Diesel Engine

In this study, a single cylinder, water-cooled, and direct injection diesel engine was utilized. The engine had a power output of 3.5 kW and operated at a rated speed of 1500 rpm. This particular engine model is widely used in rural agrarian economies, such as in countries like India, and serves as a reliable backup power supply when necessary. A wet-sump lubrication system was utilized. The camshaft was responsible for actuating the intake and exhaust valves located above the cylinder, as well as the fuel pump. Furthermore, the piston contained a hemispherical combustion chamber within its structure.

A piezoelectric transducer was installed on the surface of the cylinder head to measure the in-cylinder pressure. Additionally, the eddy current dynamometer used to load the engine entailed a crank angle encoder attached to the end. The signals collected by these sensors were transmitted to a personal computer via a data acquisition system (DAS), utilizing an NI USB 6210 device (as depicted in Plate 3.6). The acquired data were subsequently analyzed using the "Enginesoft" software which is available on the computer. The engine loading system, fuel and air flow monitoring system, and data acquisition system (DAS) were all located on the control panel (shown in Plate 3.7). Both the engine and the eddy current dynamometer were cooled using a central water cooling system. The water flow rate for the engine was set at 250 litres per hour, while for the dynamometer, it was maintained at 120 litres per hour. A visual representation of the experimental arrangement can be found in Figure 3.2.

Furthermore, the engine test rig was equipped with separate fuel tanks to ensure distinct storage for neat diesel and test fuels. An in-cylinder Kistler piezoelectric pressure transducer (model 6613CA) was installed to measure the variations in cylinder pressure throughout each engine cycle. Moreover, a crank angle encoder was mounted at the crankshaft's end to ensure accurate crank angle measurements. Detailed specifications of the Kistler pressure sensor can be found in Appendix 1. To ensure accurate temperature measurement of the combusted gases, a K-type thermocouple was placed upstream of the exhaust manifold inlet. Furthermore, the airflow rate was measured by utilizing a differential pressure sensor that was connected to orifice plates positioned at the rear of the engine control panel unit. Similarly, the fuel flow rate was determined using a calibrated 20cc standard burette, along with a stopwatch for accurate timing. To ensure proper functioning and avoid issues such as overflowing or emptying of the burette, photoelectric sensors are employed. Plate 3.6 displays photographic images of various components, including the piezoelectric pressure sensor (Image A), the airflow differential pressure sensor (Image C), and the K-type thermocouple (Image D).

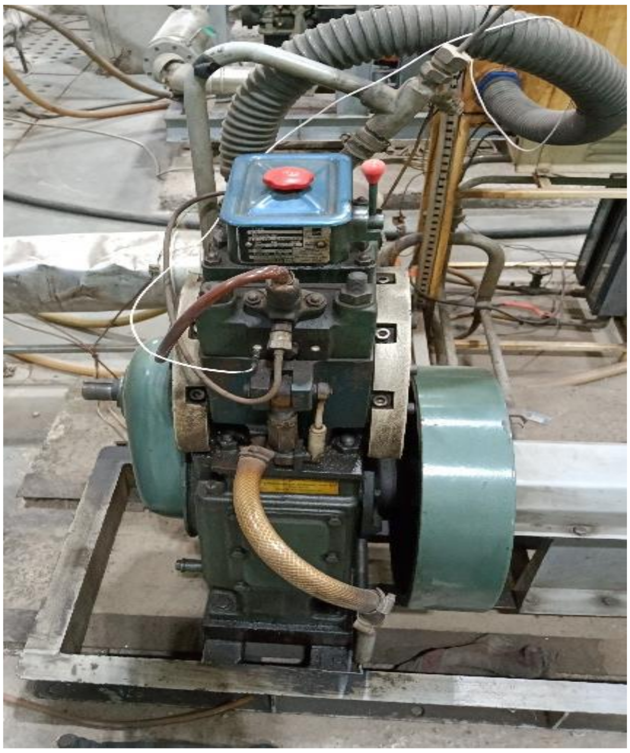

Plate 3.5: Test engine set-up

Plate 3.6: NI Data acquisition system

Plate 3.7: Control panel

Table 3.3: Specifications of the diesel engine test-setup

Make	**Kirloskar**
Model	TV1
Rated Brake Power (kW)	3.5
Rated Speed (rpm)	1500
Number of Cylinder	One
Bore X Stroke (mm)	95 x 110
Compression Ratio	17.5:1
Cooling System	Water Cooled
Lubrication System	Forced Feed
Cubic Capacity	0.78 Lit
Inlet Valve Open (Degree)	4.5 BTDC
Inlet Valve Closed (Degree)	35.5 ABDC
Exhaust Valve Open (Degree)	35.5 BBDC
Exhaust Valve Closed (Degree)	4.5 ATDC
Fuel Injection Timing (Degree)	23 BTDC

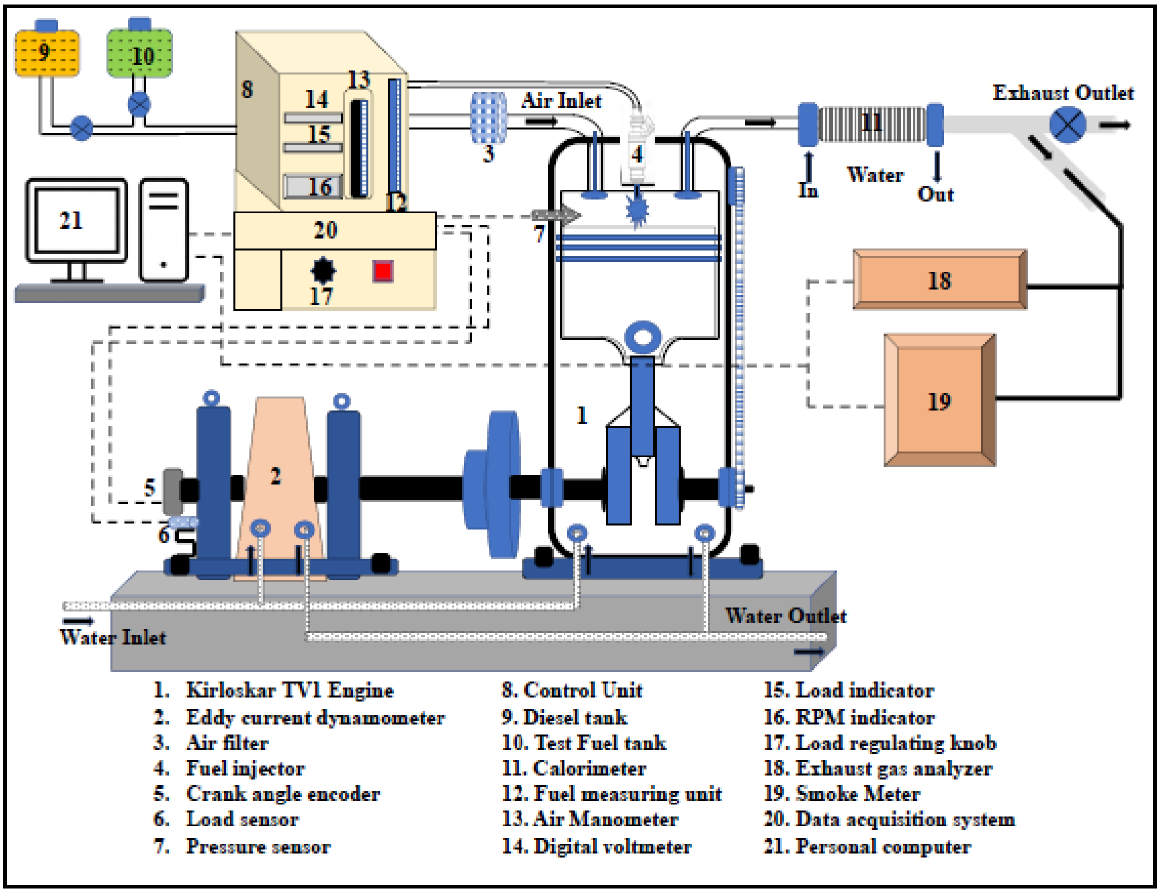

Figure. 3.2: Schematic of the engine experiment setup

3.7. SELECTION OF THE ENGINE TEST PARAMETERS

The selection of suitable test parameters holds significant importance in engine testing, and in this study, great attention was paid to their careful selection. The engine testing procedures followed the guidelines specified in IS: 10000, ensuring adherence to standardized practices. The following list provides the observed parameters during the tests, as well as the calculated parameters:

The various parameters were observed:

1) Engine load (kW)
2) Engine speed (RPM)
3) Air flow rate (kg/hr)
4) Fuel consumption rate (kg/hr)
5) Temperature (K)
6) In-cylinder pressure (bar)
7) Exhaust emissions of HC, CO, Smoke Opacity, and NOx

The parameters that were calculated are:

1) Brake specific energy consumption (BSEC)
2) Brake thermal efficiency (BTE)
3) Heat release rate (HRR)

3.7.1. MEASUREMENT OF BRAKE POWER

The measurement of BP is a crucial aspect of internal combustion engine testing. In this study, a flexible coupling was employed to connect the engine to an eddy current dynamometer, allowing for load application and accurate measurement of brake power. The eddy current dynamometer used was a water-cooled type, as depicted in Plate 3.8. It consists of a stator containing permanent electromagnets, and a rotor composed of a copper or steel disc. The coupling connects the rotor to the engine shaft. When the engine is loaded, current is passed through the electromagnets in the stator, energizing them. As the rotor rotates, the electromagnets generate eddy currents. The induced eddy currents create a magnetic field that counteracts the rotation of the rotor, resulting in a load being applied to the engine. To dissipate the heat generated during the loading process, a water circulation system was implemented on the dynamometer. The applied load on the engine was measured using a moment arm that exerted force on a load cell, as illustrated in Plate 3.9. The load applied to the engine was measured and recorded in kilograms (kg). The brake power was then computed using Equation 3.2, with the calculation incorporating an arm length of 0.185m for the dynamometer.

$$\text{BP (kW)} = \frac{2*\pi*N(rpm)*Load(kg)*9.81*Dynamometer\ arm\ length\ (m)}{60*1000} \tag{3.2}$$

Plate 3.8: Eddy current dynamometer

Plate 3.9: Load cell placed on the dynamometer

3.7.2. Measurement of Engine Speed

A toothed disc was installed at the end of the engine shaft where the dynamometer is located. In proximity to the disc, a magnetic pickup-type RPM sensor was installed, as illustrated in Plate 3.10. The RPM sensor consisted of a permanent magnet, a yoke, and a coil. As the toothed disc rotated, each tooth passing by the sensor produced a pulse in the coil through electromagnetic induction. The number of pulses increased with higher engine speeds. These pulses were then transmitted to the DAS, which analyzed the signals to calculate the engine RPM. Both the control panel and the software interface running on the computer displayed the computed RPM value.

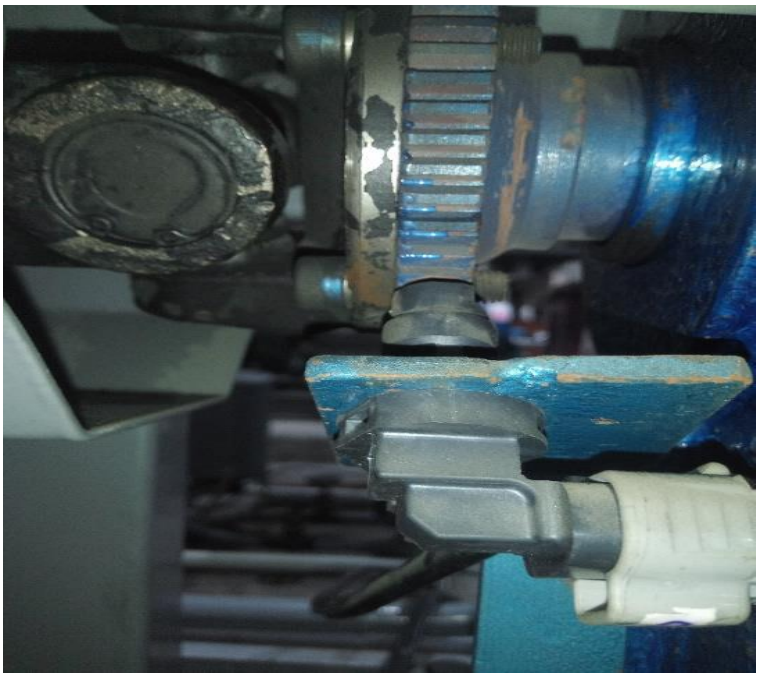

Plate 3.10: Instrument for engine speed measurement

3.7.3. Measurement of Fuel Flow

To measure the fuel consumption of the engine at different loads, a Yokogawa differential pressure transmitter from Japan was utilized. This transmitter functioned on the principle of hydrostatic head and was positioned near the burette's end, as shown in Plate 3.11. The voltage output of the transmitter was directly related to the weight of the fuel present in the column. To determine the fuel flow rate, the change in the transmitter output was measured at regular intervals and multiplied by the fuel factor (FF). The FF represents the quantity of fuel (kilograms) dispensed from the burette per unit change in the transmitter's output voltage (kilograms per volt). The calculation of the FF is described in Equation 3.3 in the study.

$$\text{Fuel Factor} = \rho * g * h * A \qquad (3.3)$$

The data acquisition system received direct signals from the sensor, enabling the accurate measurement of the fuel flow rate. Concurrently, manual readings were obtained from the burette to validate the data acquired from the sensor. By utilizing the fuel flow rate data, it becomes feasible to calculate the BTE and BSEC of the engine under a particular load. Equation 3.4 outlines the calculation of brake thermal efficiency, which quantifies the effectiveness of changing the fuel's heat into useful work at the brakes. This equation provides a formula to determine the specificefficiency. Similarly, Equation 3.5 in the study outlines the calculation of BSEC. BSEC is a metric used to quantify the energy consumed from the fuel to generate a unit of shaft power.

$$\text{BTE (\%)} = \frac{\text{BP (kW)}}{\text{massTflowTrateT(kg/s)}*\text{CalorificTvalue(kJ/kg)}} \qquad (3.4)$$

$$\text{BSEC (MJ/kWh)} = \frac{\text{mass flow rate (kg/s)}*\text{Calorific value (kJ/kg)}*3600\text{BP (kW)}}{\text{BP (kW)}} \qquad (3.5)$$

Plate 3.11: Fuel flow sensor

3.7.4. Measurement of Air Flow

Accurately calculating the airflow in an engine is challenging due to the pulsating nature of air intake, occurring once every two revolutions of the crankshaft, as well as the compressibility of air. Dependable data may not be obtained solely by relying on an orifice in the induction pipe, as its usage alone does not guarantee reliability. To overcome this, an appropriately sized air box was utilized, which incorporated a sharp-edged circular orifice for airflow measurement. A U-tube manometer was used to measure the pressure differential between the atmosphere and the air box, as depicted in Plate 3.8. Equation 3.17 was then used to calculate the mass flow rate of air, as described in the paper.

$$\text{Mass of air (kg/h)} = C_d \times \text{A} \times \sqrt[2]{2 \times g \times h_w \times \frac{q_w}{q_a}} \qquad (3.17)$$

Where C_d = co-efficient of discharge (0.6),
A = orifice area,
g= gravitational acceleration,
h_w = Pressure head (water column),
ρ_w=Density of water
ρ_a = Density of air.

Plate 3.12: Air flow sensor

Additionally, Plate 3.12 illustrates the placement of an air sensor inside the air box to accurately calculate the air flow rate. The air sensor was designed with a rotor containing blades, which assisted in the measurement process. As the air passed through the blades, they initiated rotation, and the presence of embedded metal within each blade facilitated magnetic detection, generating pulses. The signals were processed by the transmitter to determine the air flow rate. The collected data was readily accessible through the software available on the computer, offering convenient access to the acquired data.

3.7.5. Measurement of Temperature

For temperature measurement purposes in this study, K-type thermocouples constructed with chrome-alumel were employed. A digital panel metre with six channels was used to measure a variety of temperatures, including inlet air, outlet gas, coolant water entry and exit temperature, and calorimeter water inlet and outlet temperature. The thermocouples were connected to the meter, which underwent calibration using a millivolt source prior to usage. The calibration range of the meter extended up to 800°C.

3.7.6. Measurement of In-Cylinder Pressure

The measurement of in-cylinder pressure was conducted using a piezoelectric transducer manufactured by 'Kubeler'. The charge amplifier received the signals from the transducer and amplified them while cutting down on signal noise. These amplified signals were then transmitted to the DAS.

Plate 3.13: Pressure sensor installed on the engine head

By combining these signals with the data from the crank angle (CA) encoder, the DAS generated a pressure versus CA graph within the software running on computer. To ensure accurate and reliable measurements, the study recorded pressure data for every degree of crank angle rotation. To further improve accuracy, the study employed the averaging of fifty consecutive cycles to generate the in-cylinder pressure versus CA data. The placement of the pressure sensor on the engine head can be seen in Plate 3.13.

3.7.7. Measurement of Exhaust Emissions

The exhaust emissions produced by a diesel engine encompass various pollutants, which include unburnt hydrocarbons, carbon dioxide, carbon monoxide, nitrogen oxides, and smoke. The opacity of the exhaust gas can be determined as an indirect method to evaluate smoke emissions. In this particular study, an AVL smoke meter (as shown in Plate 3.14) was employed. The AVL smoke meter operates by emitting a light beam from a source and then capturing it with a receiver. As the exhaust gas passes through the light beam, smoke particles present in the gas scatter or absorb a portion of the light beam. The remaining light beam received by the photocell receiver is indicative of the smoke opacity. The photocell generates a photoelectric current upon light exposure. To measure the emissions of these exhaust gases, an AVL di-gas analyzer (Plate 3.15) was employed in this study. The di-gas analyzer, along with its technical specifications provided in Appendix III and IV, determines the concentrations of these pollutants. The emission data of these exhaust gases were subsequently converted to brake-specific emission values offline.

Plate 3.14: Smoke meter

Plate 3.15: AVL gas analyzer

3.7.8. Calculation of Heat Release Rate (HRR)

The assessment of heat release during the combustion process in a diesel engine is of great importance since it directly influences engine efficiency, power output, and emissions. For this study, the approach outlined by Heywood [50] was utilized to analyze the heat release. This approach is depends on the application of the 1st law of thermodynamics, makes no distinction during combustion between the burnt and unburned zones inside the cylinder and instead employs a simple single-zone model. While more complex multi-zone models exist, they require accurate tracking of both the unburned and burned areas in order to calculate heat transfer. Despite the challenges associated with defining the evolution of multiple zones, it has been observed that employing multi-zone models does not provide significant advantages. In this particular approach, the HRR is calculated using equation 3.18.

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma-1} * P * \frac{dv}{d\theta} + \frac{1}{\gamma-1} * V * \frac{dP}{d\theta} - \frac{dQ_W}{d\theta} \tag{3.18}$$

Where, dQ/dθ = Net heat release rate into the engine cylinder (J/°CA);
dQw/dθ = Neat transfer rate from wall (J/°CA),
γ = specific heats ratio;
P = Cylinder pressure (bar);
V = Gas volume (m^3);
θ = Crank angle (θ)

3.8. METHODOLOGY FOR ENGINE TRIALS

Essential checks must be made at the early stage of engine testing to make sure the setup is accurate and functionally sound. Prior to starting the engine in this study, validations were performed to verify the fuel level in the tank and ensure there were no air bubbles in the fuel line. Additionally, the availability of cooling water was confirmed, the lubricant level in the sump was checked, and the engine was operated under a no-load condition. After completing these inspections, The engine was turned on and operated for around 20 to 30 minutes until it reached a stable state. This duration ensured that the EGT stabilized at the designated load level. Simultaneously, the DAS was activated by establishing a connection between it and the "EngineSoft" software version 4.0, which was installed on a personal computer utilizing LabView. Once the DAS was activated, the sensors and transmitters positioned throughout the engine test setup started receiving signals. The subsequent stage involved calibrating the sensor resolution by generating a new file in Enginesoft, tailored to meet the specific requirements. In this study, the sensor values were adjusted to the minimum resolution to ensure more precise data and reduce errors. For the analysis of combustion data, an average of 60 cycles was considered, while 10 datasets were chosen to evaluate various performance parameters. The engine experiments were conducted at a consistent speed of 1500 rpm and a rated power of 3.5 kW, following the protocols specified in the IS:10000 standards and using the calibrated specifications provided by the engine manufacturer.

The primary goal of this experiment was to examine the performance and exhaust emissions of a diesel engine at various load conditions. The load settings spanned from no load to 100% of the engine's maximum load capacity, with 25% increments. To maintain accuracy and reliability, three readings were acquired at each load setting and then averaged. Before conducting the tests, the engine was given sufficient time to reach a stable operating state after each 25% increment in load. This allowed the engine to stabilize before measurements were recorded. Simultaneously, exhaust emissions were evaluated by introducing a gas analyzer and smoke meter probe into the engine effluent. Once again, the average of three readings was taken into account to determine the exhaust emissions.

All experiments were conducted under ambient temperature and pressure conditions. Initially, tests were performed using neat diesel as the base fuel for comparison. Following that, a range of fuel blends incorporating various proportions of ethanol and butanol were investigated and compared to both diesel-ethanol blends and pure diesel fuel. The experiments began with the engine running on neat diesel under no load conditions. After achieving a steady operating condition, the fuel supplied to the engine has been changed to the experimental fuel. After that, the engine was run for around 30 minutes to make sure the new fuel was stable. Measurements were recorded only when the engine achieved a stable state. The injector opening pressure was constantly held at the predetermined value throughout the experiment, and the measuring devices were routinely calibrated.

Measurements were made at each load setting while the engine load was gradually increased from no load to full load. Throughout the experiment, a number of metrics, including air flow rate, fuel flow rate, EGT, emissions of CO, HC, and

NOx, and smoke opacity, were carefully tracked and recorded. Additionally, a data acquisition system along with a personal computer was utilized to record the pressure crank angle data for 50 successive cycles. Afterwards, the collected data was analyzed to determine the average pressure variation in relation to the crank angle.

3.8.1. Experiments

- The experiments were performed using neat diesel fuel as the baseline, as well as various blends of diesel with ethanol in different proportions, as specified in Table 3.4. The combustion, performance and emission characteristics using these prepared fuels were compared to those obtained with the base fuels.
- Among the tested blends, the combination of ethanol, butanol, and diesel that demonstrated the lower BTE and the most favourable emissions was identified. To further improve engine performance and reduce emissions, different volume percentages of ethanol were incorporated into the selected fuel blend.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. INTRODUCTION

This section presents the findings of the study, beginning with an investigation into the physio-chemical properties of a blend comprising Diesel, Ethanol, and Butanol. Additionally, the influence of additives on the long-term storage stability of the blend is examined. The chapter also encompasses a thorough analysis of engine experiments conducted using Ethanol-diesel blended fuel. Detailed discussions are provided to assess the combustion, performance, and emission characteristics of the engine when utilizing Ethanol blended fuel, with a comparison made to the baseline diesel fuel.

4.2. COMPARATIVE EVALUATION OF PHYSICAL AND CHEMICAL PROPERTIES BETWEEN DIESEL AND ETHANOL-BLENDED FUEL

Both diesel fuel and the experimental test fuels were subjected to analysis to assess their physio-chemical properties. The results indicated that ethanol-blended fuel has a lower energy content compared to pure diesel fuel, primarily due to the relatively lower calorific value of ethanol.

Table 4.1: Physico-chemical Properties of Diesel and Prepared test fuel blends

Property / **Fuel sample**	**Density(kg/m^3)**	**Kinematic Viscosity at 40°C (cSt)**	**Calorific value (MJ/kg)**
D100	840	4.04	43.2
D80E10B10	830.5	3.647	40.055
D75E15B10	828	3.5135	39.24
D70E20B10	825.5	3.38	38.425
D65E25B10	823	3.2465	37.61
D60E30B10	820.5	3.113	36.795

However, these fuels exhibit a higher octane rating than pure diesel fuel, attributed to the higher octane rating of ethanol. The density of the blended fuel can also vary depending on the ethanol content. The physio-chemical properties of the different test fuels are presented in Table 4.1.

4.3. PERFORMANCE PARAMETERS OF ENGINES USING ETHANOL-DIESEL BLENDED FUEL

During the initial phase, the experiments were performed using pure diesel fuel. Subsequently, the tests were conducted using blend fuels consisting of diesel, ethanol, and butanol. The engine load was systematically adjusted in 25% increments of its maximum load capacity. This section primarily focuses on evaluating the combustion, performance, and emission characteristics of the engine while utilizing these test fuels.

4.3.1. Combustion Characteristics

The combustion process taking place in the engine cylinder has a substantial impact on both engine performance and emission characteristics. The combustion process in a compression ignition engine can be divided into four phases: (i) ignition delay (ID) stage, (ii) premixed/uncontrolled combustion, (iii) diffusion/controlled combustion, and (iv) after burning/late combustion. The formation and behaviour of the flame front during combustion also play a crucial role in diesel engine operation. The quality of fuel, air-fuel ratio, CR and combustion efficiency are among the various factors that influence the flame front. A higher flame speed promotes efficient combustion, leading to improved engine performance and reduced emissions of CO, hydrocarbons, and soot. However, the quantities of nitrogen oxides (NOx) increase due to an increase in-cylinder temperature. Conversely, an excessively high flame speed is unfavourable as it can give rise to increased pressure, noise, and detonation. Therefore, maintaining an optimal flame speed range is crucial for the efficient operation of a CI engine.

4.3.1.1. Heat Release Rate (HRR)

The HRR is a significant parameter that provides insights into the rate at which heat energy is released during the combustion of fuel at various crank angle positions throughout different combustion stages. Analyzing the HRR curve is essential for determining the occurrence of ID, SOC/EOC, and the fraction of fuel mass burned. In this experiment, the HRR was determined using the Krieger and Borman equation (3.15).

Figure 4.1 presented demonstrates the fluctuation of the HRR for ethanol-diesel blended fuel containing 10% butanol as a co-solvent without any modifications, specifically under rated power conditions. The graphs were generated for different load conditions, and for clarity, with the HRR specifically displayed at the rated power condition to ensure clarity. The outcomes show that the incorporation of ethanol up to a volume of 25% significantly enhancement in the HRR due to improved combustion behaviour resulting from better atomization. Furthermore, the figure illustrates that fuel blends such as D80E10B10, D75E15B10, D70E20B10, and D65E25B10 showcase higher heat release rates (HRR) in comparison to pure diesel fuel, whereas D60E30B10 exhibits a lower HRR. Notably, the peak HRR for these blends occurs at a distinct angle in comparison to diesel. Additionally, blends with lower ethanol content exhibit shorter combustion durations when compared to blends with higher ethanol content. It is noteworthy that the HRR increases by 8.8% for D65E15B10 and 12.9% for D55E25B10 compared to diesel, while the HRR of blends with ethanol content beyond 25% is lower due to poor atomization.

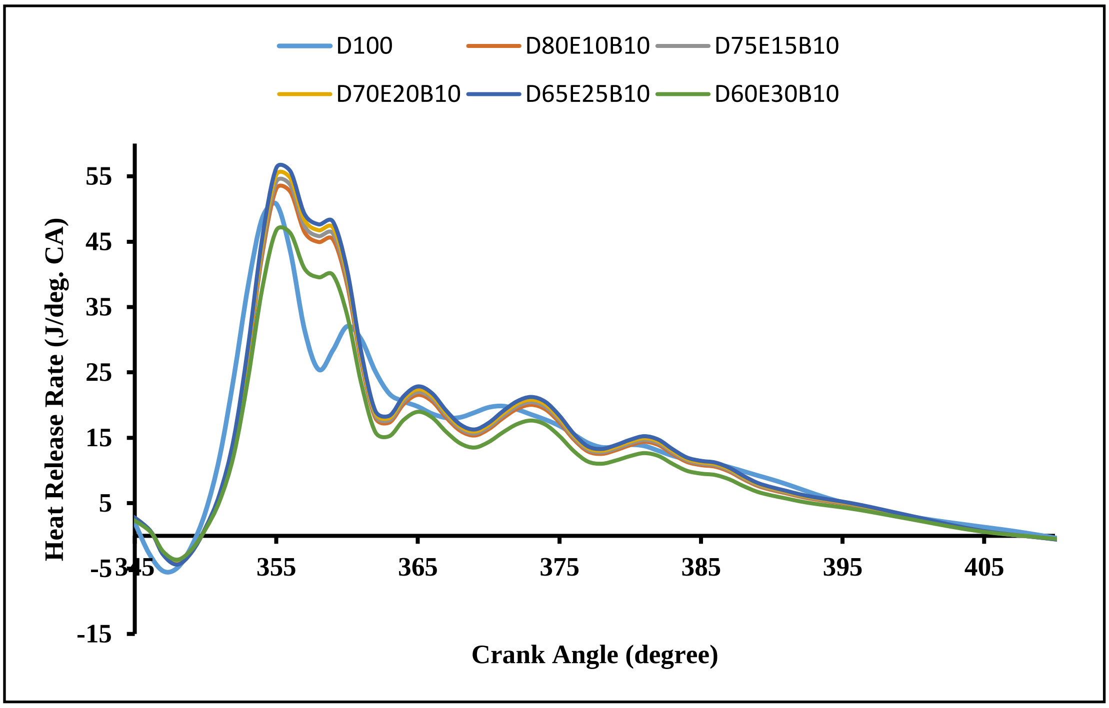

Figure 4.1: Variation in heat release rate at full load

4.3.1.2. In-Cylinder Pressure (P-THETA CURVE)

An important characteristic for comprehending the combustion process taking place within the engine cylinder, a crucial aspect involves analyzing the in-cylinder pressure. Rapid variations in pressure and temperature gradients occur during different combustion phases, requiring detailed analysis to optimize the performance and emission characteristics of engines. Typically, when the piston reaches the TDC at the end of the compression stroke, the in-cylinder pressure reaches its maximum, indicating the completion of premixed combustion. Following that, during the expansion stroke associated with the diffusion phase, the pressure within the cylinder begins to decrease and reaches its lowest value when the piston reaches the BDC. To capture the fluctuations in-cylinder pressure at various crank angle positions, a pressure transducer device is installed at the cylinder head, as described in Chapter 3.

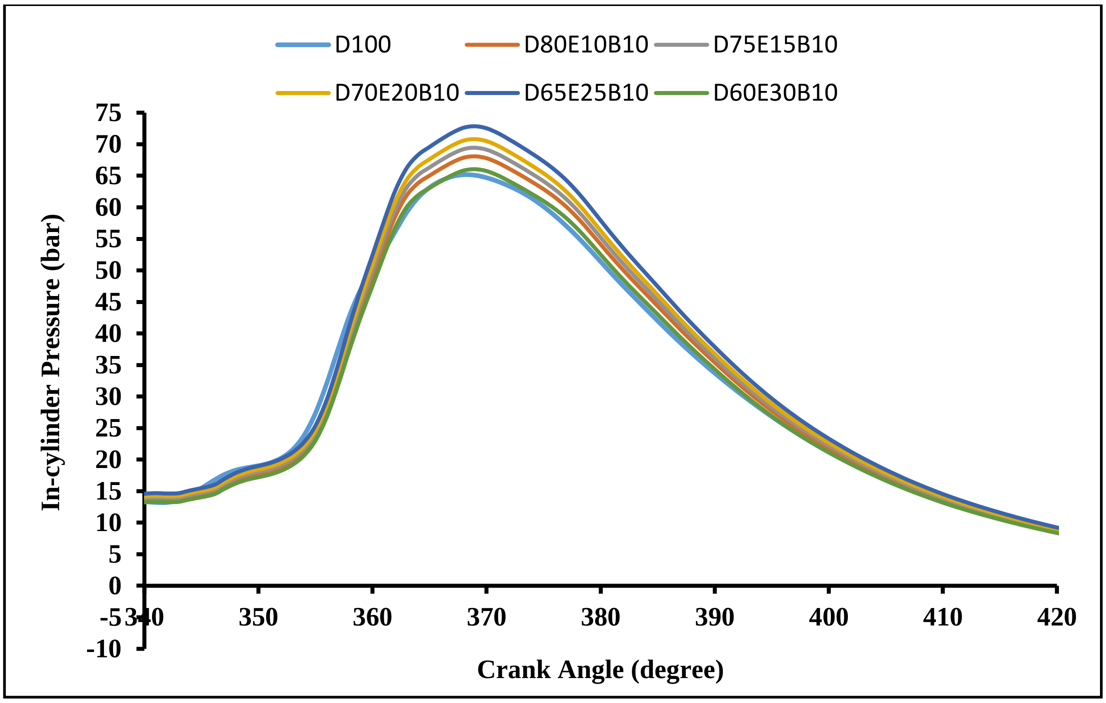

Figure 4.2: Variation in in-cylinder pressure at full load

The results depicted in Figure 4.2 indicate that certain blend fuels, namely D80E10B10, D75E15B10, D70E20B10, and D65E25B10, exhibit higher in-cylinder pressure as compared to diesel. This improvement can be attributed to the enhanced combustion efficiency achieved through the addition of ethanol in these blends. However, the blended fuel D60E30B10 demonstrates lower in-cylinder pressure than diesel. This discrepancy can be ascribed to the suppressive influence of the elevated ethanol content in the blends, stemming from its higher heat of vaporization. Moreover, as illustrated in Figure 4.2, it is observed that the peak in-pressure values of D80E10B10 and D65E25B10 are 6.5% and 14.8% higher, respectively, compared to diesel.

4.3.2. Performance Characteristics

4.3.2.1. Variation of Brake Thermal Efficiency (BTE)

The BTE serves as a metric to evaluate the efficiency of an engine in converting the chemical energy of fuel into useful work.

Figure 4.3 demonstrates the fluctuations in BTE for various fuels under various loading conditions, spanning from no load to 100% load of rated load. Notably, the blends D80E10B10, D75E15B10, D70E20B10, and D65E25B10 showcase as comparable BTE in comparison with diesel across all loads. This is attributed to the increased volatility and improved spray characteristics of the fuel blends, up to a certain ethanol content even at lower CV of test fuels. The D60E30B10 blend exhibits a highest diminished in BTE than all other test fuels. This can be attributed to the decreased self-ignition characteristics of the blend, which are a result of its higher ethanol content and the associated increase in heat of vaporization.

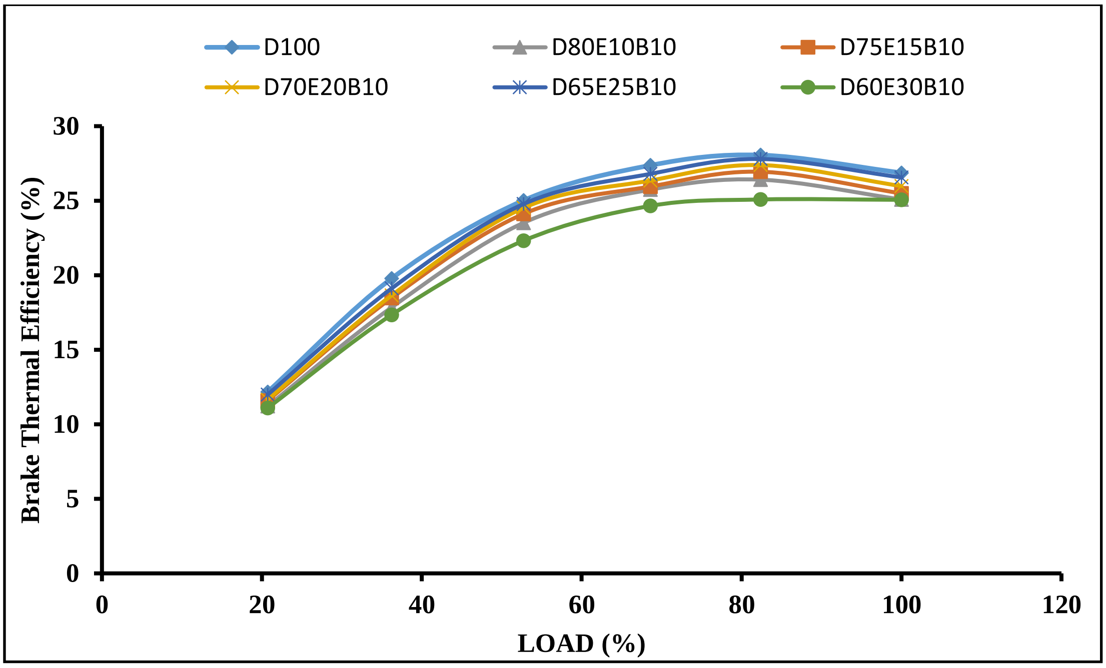

Figure 4.3: Brake thermal efficiency at various Loads

Consequently, this induces a cooling effect within the cylinder, leading to lowered temperatures and subsequently affecting the reaction of oxygen with the fuel, thereby impeding combustion. The minimum decrease in BTE for D80E25B10 is 0.6 %, while the maximum decrease for D65E30B10 is 5.2% compared to diesel.

4.3.2.2. Variation of Brake Specific Energy Consumption (BSEC)

The assessment of fuel consumption plays a crucial role in comprehending the engine performance of various fuels. Traditionally, the measurement of BSFC has been utilized as a parameter to quantify the relationship between the fuel mass flow rate and the generated brake power. However, when test fuels exhibit significant variations in calorific values and densities, BSFC may not be considered a reliable indicator. Due to its enhanced reliability, BSEC is regarded as a more

dependable approach for comparing volumetric fuel consumption.

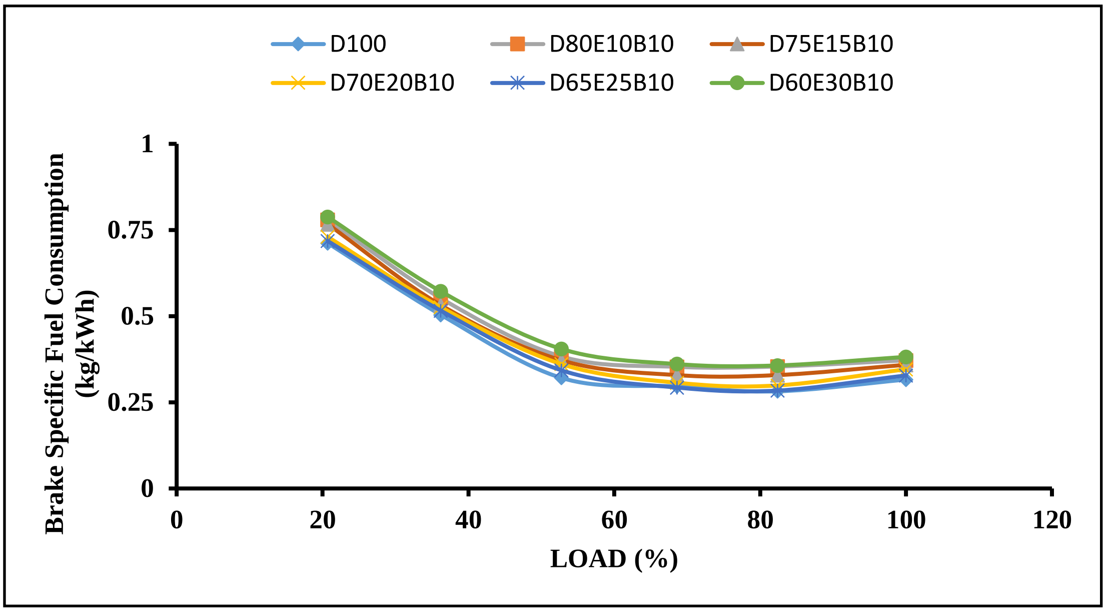

Figure 4.4: Brake Specific Fuel Consumption at various various Loads

Figure 4.4 illustrates the BSEC of the test fuels at various loading conditions: 25%, 50%, 75%, and full load. A noticeable observation is that all the fuel blends demonstrate higher BSFC in comparison to diesel across all load conditions. Among the blends, D80E10B10, D75E15B10, D70E20B10, and D65E25B10 exhibit lower BSFC compared to D60E30B10.

The engine's power can be sustained at a consistent level when using various fuel blends, albeit with a slight rise in fuel consumption. However, as the ethanol proportion in the blends rises, fuel consumption also increases. The maximum increment in BSFC is observed for D60E30B10, with a 9.1% increase, while the minimum increment is seen for D65E25B10, with a 4.2% increase compared to diesel. The increase in fuel consumption can be attributed to the lower heating value of ethanol compared to pure diesel., which also demonstrates a similar trend of increasing fuel consumption with the proportionate rise in ethanol percentage within the blends. Similar trends in fuel consumption can also be observed when the engine operates at 1500 rpm under different load conditions.

4.3.2.3. Variation In Exhaust Gas Temperature (EGT)

EGT holds significant importance as an operational parameter for CI engines, as it actively regulates the emission of harmful gases discharged during the combustion process.

Figure 4.5 illustrates the variation in EGT among the fuel blends and diesel across different load conditions. It is evident that all the fuel blends exhibited higher EGT than diesel at all loading conditions except D60E30B10.

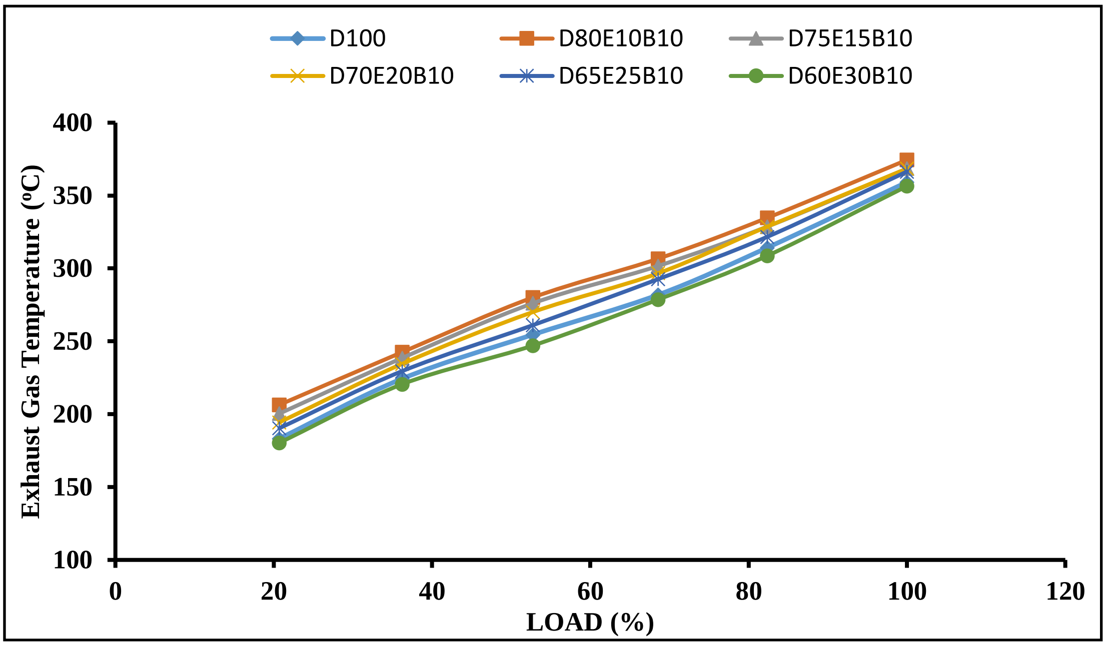

Figure 4.5: Exhaust gas temperature at various Loads

Specifically, blends D80E10B10, D75E15B10, D70E20B10, and D65E25B10 demonstrated higher EGT values than that of diesel. Conversely, the fuel blend D60E30B10 resulted in lower EGT than other test fuels. The lower EGT observed in blends with a higher volume of ethanol can be attributed to the cooling effect caused by the higher prevalence of heat of vaporization within these blends. This cooling effect in the in-cylinder environment reduces the reaction rate between fuel particles and available oxygen, resulting in lower EGT. The maximum increase in EGT for D65E10B10 is 9.1%, while the maximum decrease in EGT for D60E30B10 is 4.2% compared to diesel.

4.3.3. Emission Characteristics

This section discusses the process by which exhaust emissions are generated in a diesel engine and examines the impact of blended fuels on their formation and control. The analysis concentrates on examining the emissions of NOx, HC, CO, and smoke opacity throughout the combustion of different fuels. The engine loads ranges from 25% to 100% to study the emissions under a consistent speed of 1500 rpm. The measurements of exhaust emissions were conducted using a smoke meter and an AVL gas analyzer installed at the exhaust of the engine. The assessment was performed based on a brake-specific (g/kWh) approach, taking into account the varying fuel compositions. This allows for a comparison of the emissions produced by different fuel blends and additives.

4.3.3.1. Unburnt Hydrocarbon (UBHC) emissions

Unburnt hydrocarbon pollutants are formed when fuel particles do not participate in the combustion process and are released into the exhaust without being fully processed. The level of unburnt hydrocarbon emissions can be considered an indicator of the combustion quality within the engine. Several factors like fuel composition, combustion reaction time, combustion temperature, cylinder crevices, oxygen availability, and engine configuration can influence the formation of unburnt hydrocarbon emissions in diesel engines.

Figure 4.6 demonstrates that the blend containing 30% ethanol content displays elevated hydrocarbon (HC) emissions, whereas the blends comprising 25% ethanol content exhibit reduced HC emissions than diesel. This variation can be attributed to the distinctive combustion characteristics of the blends. Blends with lower ethanol volume tend to have improved combustion characteristics, while blends with higher ethanol volume exhibit reduced combustion characteristics.

Moreover, it is evident that D75E25B10 and D65E10B10 result in 12.8% and 7.9% lower hydrocarbon (HC) emissions compared to diesel, respectively.

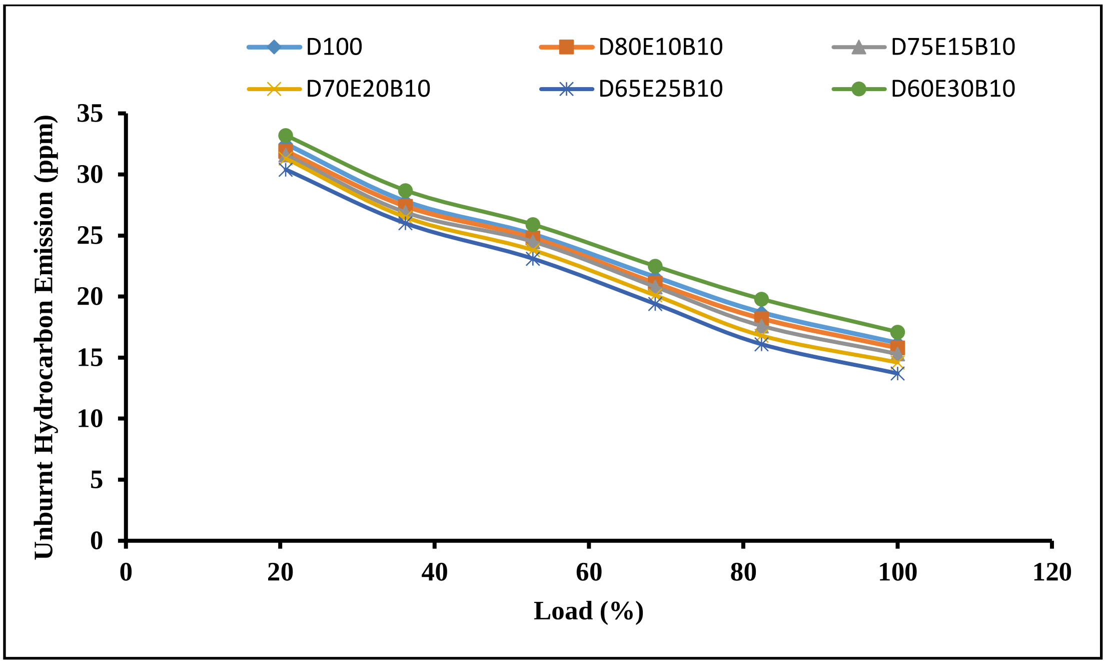

Figure 4.6: Unburned hydrocarbons emission at various Loads

4.3.3.2. Carbon Monoxide (CO) emissions

CO is generated as an outcome of the incomplete combustion of carbon-based fuels within the combustion chamber. Vehicular exhaust is a noteworthy source of CO emissions in the atmosphere. In contrast to other exhaust gases, carbon monoxide (CO) is known for its high stability and ability to endure in the atmosphere for prolonged durations, presenting a notable environmental risk.

Figure 4.7 depicts the relationship between CO emissions and brake power. The amount of CO emitted from a CI engine provides insights into combustion efficiency, in-cylinder temperature, oxygen availability, and the self-ignition characteristics of the fuel used. In this research, various blends comprising 10%, 15%, 20%, 25%, and 30% ethanol were utilized, which possess higher Lower Heating Values (LHV). As a result, the incorporation of higher ethanol volumes leads to reduced in-cylinder temperatures, which, in turn, contribute to elevated CO emissions in comparison to diesel. The figure illustrates that blends with lower ethanol content exhibit reduced CO emissions, while those with higher ethanol content exhibit higher CO emissions. This can be ascribed to the enhanced physical and chemical properties observed in blends with lower ethanol content (up to 25%), which facilitate improved atomization and volatility. These factors contribute to more complete combustion, thereby decreasing CO emissions in comparison to diesel. However, when ethanol is introduced beyond the threshold of 25%, it significantly increases the LHV, leading to a cooling effect within the cylinder. Consequently, this cooling effect results in more CO emissions. This is further influenced by the slower reactivity of oxygen with the fuel during combustion. The reduction in CO emissions for D75E10B10 and D65E25B10 amounts to 3.2% and 7.8% respectively, while the increase in CO emissions for D55E30B10 is 4% compared to diesel.

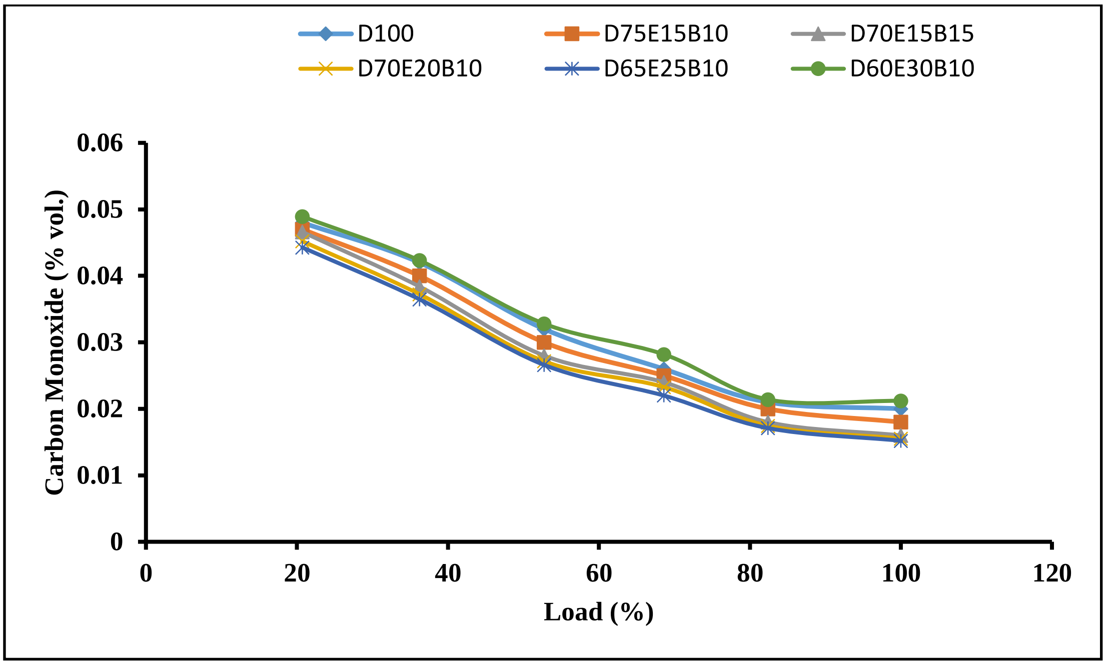

Figure 4.7 Carbon monoxide emission at various Loads

4.3.3.3. Nitrogen Oxide (NOx) emissions

Nitrogen oxide emissions are highly detrimental pollutants associated with compression ignition (CI) engines, posing significant risks to both human health and the environment. Prolonged exposure to NOx emissions can lead to severe respiratory and cardiovascular issues. Moreover, NOx contributes to the formation of smog, brown clouds, acid rain, and ground-level ozone depletion, causing harm to flora, fauna, and ecosystems.

The formation of NOx in CI engines can be attributed to three main mechanisms: thermal NOx, prompt NOx and fuel NOx. Thermal NOx formation is primarily influenced by the temperature of the exhaust gases during combustion. The existence of oxygen aids in achieving higher exhaust temperatures, which in turn promotes combustion and allows for an adequate duration for high-temperature reactions. Nanoparticles possessing excellent heat dissipation properties can effectively mitigate the formation of thermal NOx.

Fuel NOx arises from the nitrogen molecules present in the fuel, which contribute to NOx formation. Conversely, the formation of nitrogen oxides (NOx) at an early stage is unavoidable and takes place when atmospheric nitrogen reacts with combustion products within the fuel-rich zone. However, in compression-ignition engines, the primary factor contributing to NOx formation is the chemical reactions occurring at high temperatures, in accordance with the extended Zeldovich mechanism.

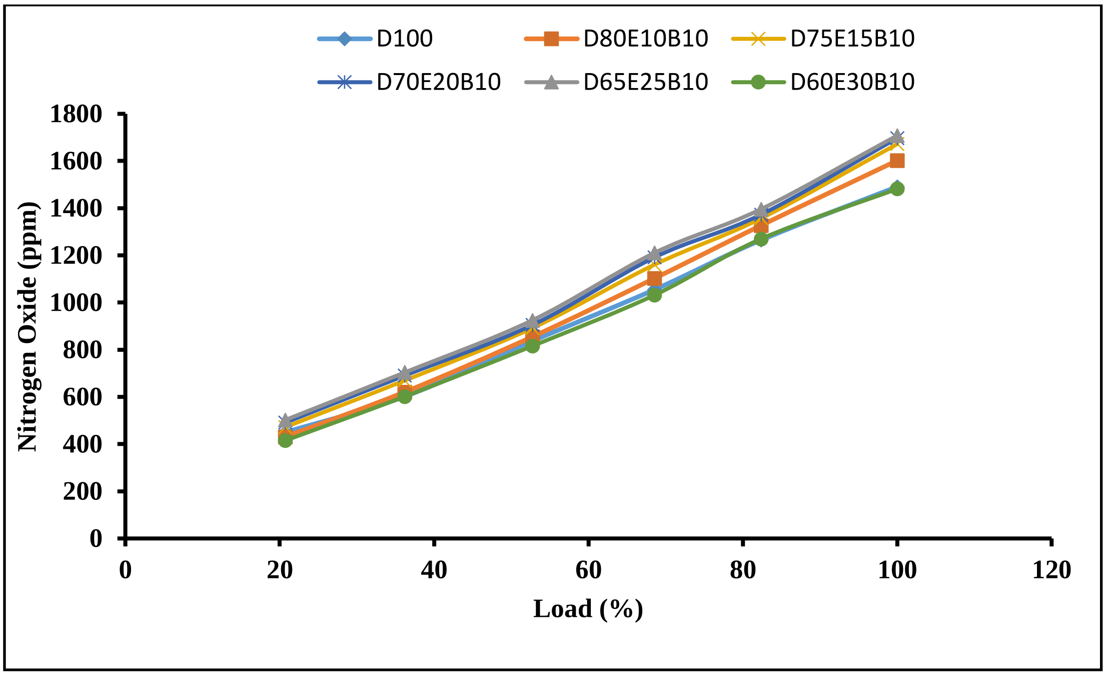

Figure. 4.8 NOx emission at various Loads

Addressing NOx emissions in CI engines is crucial for mitigating the adverse impacts on human health and the environment. By understanding the different mechanisms of NOx formation, strategies can be developed to control and reduce NOx emissions effectively.

Figure 4.8 illustrates the fluctuations in NOx emissions for different fuel blends under various load conditions. Significantly, blends with lower ethanol content (below 25%) exhibit higher levels of NOx emissions, while blends with higher ethanol content (above 25%) demonstrate decreased NOx emissions in comparison to diesel. This can be attributed to the higher combustion temperatures associated with blends containing lower ethanol content and the lower combustion temperatures associated with blends containing higher ethanol content. The incorporation of ethanol up to a specific level enhances the volatility, self-ignition, and atomization characteristics of the fuel blends within the combustion chamber. This enhancement is attributed to the higher LHV exhibited by ethanol, which effectively reduces the combustion temperature. Specifically, the blends D75E10B10 and D65E25B10 exhibit NOx emissions that are 2.8% and 7.8% higher than diesel, respectively. In contrast, the D55E30B10 blend shows significantly lower NOx emissions than diesel. In general, all the blends generate higher NOx emissions in comparison to diesel. The decrease in NOx emissions observed in the D45E30B10 blend at various load conditions can be attributed to the lower temperature inside the combustion chamber, which is a result of the higher LHV and lower CV of the blend.

4.3.3.4. Smoke Opacity (%)

It serves as an indirect indicator of the amount of soot present in engine exhaust emissions, with soot being the primary constituent of particulate matter. Soot formation occurs when long-chain hydrocarbons undergo thermal cracking in an oxygen-deficient environment.

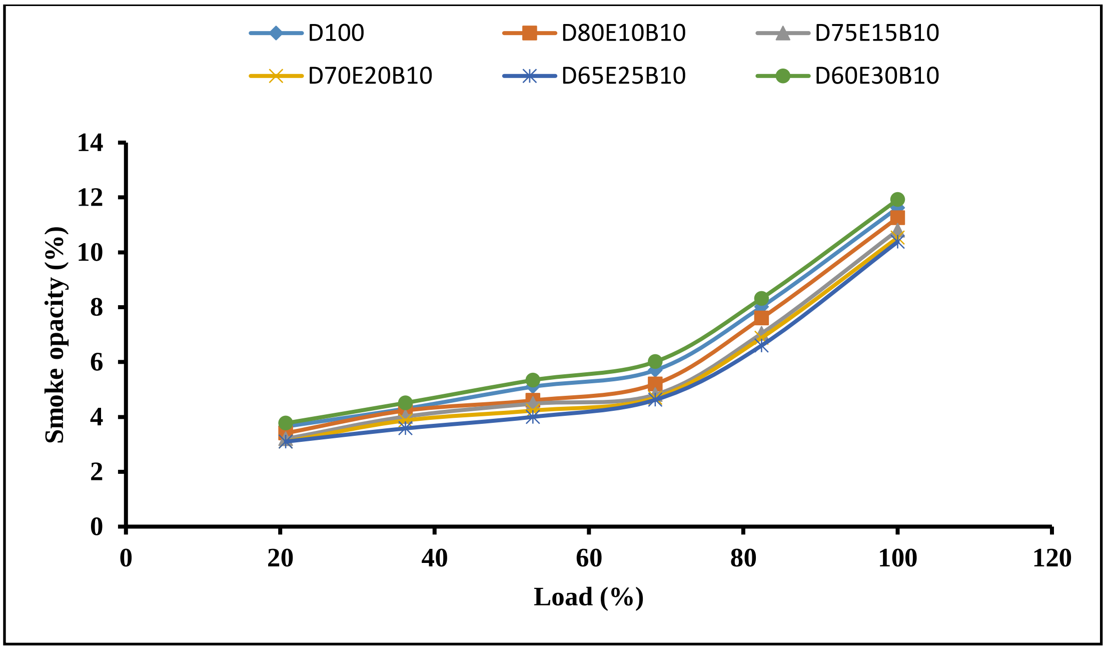

Figure. 4.9 Smoke opacity at various Loads

Consequently, a reduction in the air-fuel ratio leads to an elevation in smoke opacity in diesel engines. Based on the data presented in Figure 4.9, it is evident that the blend D65E25B10 demonstrates reduced smoke emissions in comparison to the other blends. This enhancement can be attributed to the improved combustion characteristics observed in the ethanol-containing blend up to a certain percentage. The incorpoation of ethanol enhances the evaporation rate, leading to a shorter combustion duration and higher temperatures. Due to this improved combustion process, lower smoke emissions are observed compared to both diesel and other test fuels. However, when the ethanol content surpasses 25%, the higher LHV limits the combustion temperature, resulting in reduced temperatures within the cylinder. These lower temperatures decrease the reactivity of oxygen and contribute to higher smoke emissions. This clarifies why blends such as D55E30B10 exhibit elevated smoke emissions in contrast to diesel.

CHAPTER 5

CONCLUSION AND FUTURE WORK

Conclusions

This study aimed to assess the practicality of incorporating diesel-ethanol blended fuels containing Butanol into an unaltered diesel engine. The primary objective was to assess the viability of Ethanol as a fuel option for a CI engine and examine its impact on combustion, performance, and emission attributes. The obtained experimental outcomes of this investigation are promising, and the primary discoveries can be outlined as follows:

1. The engine's combustion, performance, and emission characteristics can be enhanced by blending up to 25% ethanol into diesel fuel, along with the addition of 10% butanol as an additive.
2. The presence of ethanol in diesel fuel leads to a higher LHV, resulting in an ignition delay. This ID improves the combustion process by facilitating proper fuel-air mixing.
3. Compared to diesel, the combustion process in ethanol-blended fuel results in increased peak in-cylinder pressure and HRR. This improvement in the combustion process leads to enhanced performance in terms of peak cylinder pressure and HRR.
4. When the engine was fueled with ethanol-blended fuels, the thermal efficiency of the engine was as comparable or slightly lower than diesel and the BSEC of the engine was increased. This indicates that the engine achieved a better conversion of fuel energy into useful work and had a higher energy consumption rate when running on ethanol blends.
5. The engine emitted higher levels of nitrogen oxides (NOx) throughout the experimental range compared to diesel fuel. This is a significant emission characteristic of plant oil. Various methods, including EGR, can be employed to mitigate these NOx emissions and reduce their impact.

6. The emissions of CO, Hydrocarbon, and Smoke from the ethanol-blended fuel were consistently lower than those from the diesel fuel throughout the entire experimental range.
7. The study's findings suggest that incorporating fuel additives into diesel-ethanol blends can yield considerable advantages and better environmental outcomes, and may serve as a viable alternative fuel for CI engines in the future.

Scope for Future Work

However, more studies are required to determine the optimal blend ratios and engine operating conditions that can maximize the benefits of using ethanol and other alcohol additives in diesel engines, such as improving fuel efficiency, reducing emissions, and minimizing engine wear and tear. The impact of the long-term use of butanol on engine durability and reliability also needs to be investigated. Despite these challenges, the potential benefits of using butanol as an additive for ethanol-diesel blends in diesel engines make it a promising area for future research and development.

Further research and optimization are needed to fully understand its potential and overcome any drawbacks related to fuel consumption.

REFERENCES

[1] "https://ourworldindata.org/energy#citation."

[2] "Energy - Our World in Data." https://ourworldindata.org/energy#citation (accessed May 28, 2023).

[3] "World Energy Outlook 2018 – Analysis - IEA." https://www.iea.org/reports/world-energy-outlook-2018 (accessed May 28, 2023).

[4] "India Energy Outlook 2021 – Analysis - IEA." https://www.iea.org/reports/india-energy-outlook-2021 (accessed May 28, 2023).

[5] "Ministry of Coal, Government of India." https://coal.nic.in/en/major-statistics/coal-indian-energy-choice (accessed May 28, 2023).

[6] "Perform, Achieve, Trade (PAT) Scheme – Policies - IEA." https://www.iea.org/policies/1780-perform-achieve-trade-pat-scheme (accessed May 28, 2023).

[7] İ. A. Reşitoğlu, K. Altinişik, and A. Keskin, "The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems," *Clean Technol Environ Policy*, vol. 17, no. 1, pp. 15–27, Jan. 2015, doi: 10.1007/s10098-014-0793-9.

[8] R. Prasad and V. R. Bella, "A Review on Diesel Soot Emission, its Effect and Control," *BULLETIN OF CHEMICAL REACTION ENGINEERING AND CATALYSIS*, vol. 5, no. 2, Jan. 2011, doi: 10.9767/bcrec.5.2.794.69-86.

[9] A. Demirbas, A. Bafail, W. Ahmad, and M. Sheikh, "Biodiesel production from non-edible plant oils," *Energy Exploration & Exploitation*, vol. 34, no. 2, pp. 290–318, Mar. 2016, doi: 10.1177/0144598716630166.

[10] T. Mizik and G. Gyarmati, "Three Pillars of Advanced Biofuels' Sustainability," *Fuels*, vol. 3, no. 4, pp. 607–626, Oct. 2022, doi: 10.3390/fuels3040037.

[11] S. Tamalampudi and H. Fukuda, "Biodiesel," in *Comprehensive Biotechnology*, Elsevier, 2011, pp. 63–70. doi: 10.1016/B978-0-08-088504-9.00163-X.

[12] A. K. Agarwal, "Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines," *Prog Energy Combust Sci*, vol. 33, no. 3, pp. 233–271, Jun. 2007, doi: 10.1016/j.pecs.2006.08.003.

[13] T. J. Deka, A. I. Osman, D. C. Baruah, and D. W. Rooney, "Methanol fuel production, utilization, and techno-economy: a review," *Environ Chem Lett*, vol. 20, no. 6, pp. 3525–3554, Dec. 2022, doi: 10.1007/s10311-022-01485-y.

[14] B.-Q. He, S.-J. Shuai, J.-X. Wang, and H. He, “The effect of ethanol blended diesel fuels on emissions from a diesel engine,” *Atmos Environ*, vol. 37, no. 35, pp. 4965–4971, Nov. 2003, doi: 10.1016/j.atmosenv.2003.08.029.

[15] Z. Wei, Y. Zhang, Q. Xia, Y. Liu, and Y. Xu, “A simulation of ethanol substitution rate and EGR effect on combustion and emissions from a high-loaded diesel/ethanol dual-fuel engine,” *Fuel*, vol. 310, p. 122310, Feb. 2022, doi: 10.1016/j.fuel.2021.122310.

[16] Z. Chen, J. He, H. Chen, L. Geng, and P. Zhang, “Comparative study on the combustion and emissions of dual-fuel common rail engines fueled with diesel/methanol, diesel/ethanol, and diesel/n-butanol,” *Fuel*, vol. 304, p. 121360, Nov. 2021, doi: 10.1016/j.fuel.2021.121360.

[17] J. C. Ge, G. Wu, and N. J. Choi, “Comparative study of pilot–main injection timings and diesel/ethanol binary blends on combustion, emission and microstructure of particles emitted from diesel engines,” *Fuel*, vol. 313, p. 122658, Apr. 2022, doi: 10.1016/j.fuel.2021.122658.

[18] P. Saravanan, N. M. Kumar, M. Ettappan, R. Dhanagopal, and J. Vishnupriyan, “Effect of exhaust gas re-circulation on performance, emission and combustion characteristics of ethanol-fueled diesel engine,” *Case Studies in Thermal Engineering*, vol. 20, p. 100643, Aug. 2020, doi: 10.1016/j.csite.2020.100643.

[19] R. Shanmugam, P. Murugesan, G. G. Guye, and B. Duraisamy, “Effect of additives on the stability of ethanol-diesel blends for IC engine application,” *Environmental Science and Pollution Research*, vol. 28, no. 10, pp. 12153–12167, Mar. 2021, doi: 10.1007/s11356-020-10934-6.

[20] U. Asad, P. S. Divekar, and M. Zheng, “High efficiency ethanol–diesel dual-fuel combustion: Analyses of performance, emissions and thermal efficiency over the engine load range,” *Fuel*, vol. 310, p. 122397, Feb. 2022, doi: 10.1016/j.fuel.2021.122397.

[21] S. K. Yoon, “Investigation on the Combustion and Emission Characteristics in a Diesel Engine Fueled with Diesel-Ethanol Blends,” *Applied Sciences*, vol. 12, no. 19, p. 9980, Oct. 2022, doi: 10.3390/app12199980.

[22] Z. Gao, S. Lin, J. Ji, and M. Li, “An experimental study on combustion performance and flame spread characteristics over liquid diesel and ethanol-diesel blended fuel,” *Energy*, vol. 170, pp. 349–355, Mar. 2019, doi: 10.1016/j.energy.2018.12.130.

[23] J. Lin, G. Gaustad, and T. A. Trabold, “Profit and policy implications of producing biodiesel–ethanol–diesel fuel blends to specification,” *Appl Energy*, vol. 104, pp. 936–944, Apr. 2013, doi: 10.1016/j.apenergy.2012.11.049.

[24] A. O. Emiroğlu and M. Şen, “Combustion, performance and emission characteristics of various alcohol blends in a single cylinder diesel engine,” *Fuel*, vol. 212, pp. 34–40, Jan. 2018, doi: 10.1016/j.fuel.2017.10.016.

[25] J. Lee, S. Lee, and S. Lee, “Experimental investigation on the performance and emissions characteristics of ethanol/diesel dual-fuel combustion,” *Fuel*, vol. 220, pp. 72–79, May 2018, doi: 10.1016/j.fuel.2018.02.002.

[26] A. Taghizadeh-Alisaraei and A. Rezaei-Asl, “The effect of added ethanol to diesel fuel on performance, vibration, combustion and knocking of a CI engine,” *Fuel*, vol. 185, pp. 718–733, Dec. 2016, doi: 10.1016/j.fuel.2016.08.041.

[27] C. Sayin, “Engine performance and exhaust gas emissions of methanol and ethanol–diesel blends,” *Fuel*, vol. 89, no. 11, pp. 3410–3415, Nov. 2010, doi: 10.1016/j.fuel.2010.02.017.

[28] D. Hansdah and S. Murugan, “Bioethanol fumigation in a DI diesel engine,” *Fuel*, vol. 130, pp. 324–333, Aug. 2014, doi: 10.1016/j.fuel.2014.04.047.

[29] Y. Ren *et al.*, “Combustion and emissions of a DI diesel engine fuelled with diesel-oxygenate blends,” *Fuel*, vol. 87, no. 12, pp. 2691–2697, Sep. 2008, doi: 10.1016/j.fuel.2008.02.017.

[30] M. Abu-Qudais, O. Haddad, and M. Qudaisat, “The effect of alcohol fumigation on diesel engine performance and emissions,” *Energy Convers Manag*, vol. 41, no. 4, pp. 389–399, Mar. 2000, doi: 10.1016/S0196-8904(99)00099-0.

[31] Y. Putrasari, A. Nur, and A. Muharam, “Performance and Emission Characteristic on a Two Cylinder DI Diesel Engine Fuelled with Ethanol-Diesel Blends,” *Energy Procedia*, vol. 32, pp. 21–30, 2013, doi: 10.1016/j.egypro.2013.05.004.

[32] R. F. Britto and C. A. Martins, “Emission analysis of a Diesel Engine Operating in Diesel–Ethanol Dual-Fuel mode,” *Fuel*, vol. 148, pp. 191–201, May 2015, doi: 10.1016/j.fuel.2015.01.008.

[33] A. Jamrozik, W. Tutak, M. Pyrc, M. Gruca, and M. Kočiško, “Study on co-combustion of diesel fuel with oxygenated alcohols in a compression ignition dual-fuel engine,” *Fuel*, vol. 221, pp. 329–345, Jun. 2018, doi: 10.1016/j.fuel.2018.02.098.

[34] T. K. Sahu, R. Kshatri, A. Kumar, and P. C. Shukla, “Combustion Stability Investigation of Ethanol Blends (E05, E10) in a Twin-cylinder CI Engine,” Mar. 2022. doi: 10.4271/2022-01-0521.

[35] J. S. Rosa, G. D. Telli, C. R. Altafini, and L. A. O. Rocha, “Exergy analysis of a water cooled single cylinder dual fuel engine fueled with diesel-ethanol under different ethanol energy ratio,” Feb. 2022. doi: 10.4271/2021-36-0043.

[36] V. B. Pedrozo, I. May, W. Guan, and H. Zhao, “High efficiency ethanol-diesel dual-fuel combustion: A comparison against conventional diesel combustion from low to full engine load,” *Fuel*, vol. 230, pp. 440–451, Oct. 2018, doi: 10.1016/j.fuel.2018.05.034.

[37] N. Giramondi, A. Jäger, S. K. Mahendar, and A. Erlandsson, “Combustion Characteristics, Performance and NO $_x$ Emissions of a Heavy-Duty Ethanol-Diesel Direct Injection Engine,” Sep. 2020. doi: 10.4271/2020-01-2077.

[38] M. Vargün and A. N. Özsezen, “Investigation of Effect of Dual Fuel Injection Stages on Combustion Parameters in a Diesel Engine Using Ethanol-Butan-2-ol-Fossil Diesel Blends,” *Arab J Sci Eng*, vol. 47, no. 7, pp. 9173–9185, Jul. 2022, doi: 10.1007/s13369-021-06441-6.

[39] J. Huang, Y. Wang, S. Li, A. P. Roskilly, H. Yu, and H. Li, “Experimental investigation on the performance and emissions of a diesel engine fuelled with ethanol–diesel blends,” *Appl Therm Eng*, vol. 29, no. 11–12, pp. 2484–2490, Aug. 2009, doi: 10.1016/j.applthermaleng.2008.12.016.

[40] O. Nilaphai, K. Komanee, and S. Chuepeng, “Expansion heat release and thermal efficiency of acetone-butanol-ethanol-diesel blended fuel (ABE20) combustion in piston engine,” *Fuel*, vol. 309, p. 122214, Feb. 2022, doi: 10.1016/j.fuel.2021.122214.

[41] K. Theinnoi, B. Sawatmongkhon, T. Wongchang, E. Sukjit, and S. Chuepeng, “The Combustion Characteristic of Fuel Additives with Diesel–Ethanol Fuel blends on Engine Performance.” Jan. 24, 2020. Accessed: May 28, 2023. [Online]. Available: https://www.sae.org/publications/technical-papers/content/2019-32-0611/

[42] Q. Zhu *et al.*, “Evaluating the effect of n-butanol additive on particulate matter emission in diesel engine,” *Fuel*, vol. 332, p. 126003, Jan. 2023, doi: 10.1016/j.fuel.2022.126003.

[43] M. R. Atelge, “Experimental study of a blend of Diesel/Ethanol/n-Butanol with hydrogen additive on combustion and emission and exegetic evaluation,” *Fuel*, vol. 325, p. 124903, Oct. 2022, doi: 10.1016/j.fuel.2022.124903.

[44] A. I. El-Seesy, H. Hassan, L. Ibraheem, Z. He, and M. E. M. Soudagar, “Combustion, emission, and phase stability features of a diesel engine fueled by Jatropha/ethanol blends and n-butanol as co-solvent,” *Int J Green Energy*, vol. 17, no. 12, pp. 793–804, Sep. 2020, doi: 10.1080/15435075.2020.1798770.

[45] K. Ahmad and P. Saini, “Effect of butanol additive with mango seed biodiesel and diesel ternary blends on performance and emission characteristics of diesel engine,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 44, no. 4, pp. 9988–10005, Dec. 2022, doi: 10.1080/15567036.2022.2143954.

[46] N. Yilmaz and A. Atmanli, “Experimental evaluation of a diesel engine running on the blends of diesel and pentanol as a next generation higher alcohol,” *Fuel*, vol. 210, pp. 75–82, Dec. 2017, doi: 10.1016/j.fuel.2017.08.051.

[47] C. A. Cardona and Ó. J. Sánchez, “Fuel ethanol production: Process design trends and integration opportunities,” *Bioresour Technol*, vol. 98, no. 12, pp. 2415–2457, Sep. 2007, doi: 10.1016/j.biortech.2007.01.002.

[48] S. A. Jambo, R. Abdulla, S. H. Mohd Azhar, H. Marbawi, J. A. Gansau, and P. Ravindra, “A review on third generation bioethanol feedstock,” *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 756–769, Nov. 2016, doi: 10.1016/j.rser.2016.07.064.

[49] S. Chakraborty, P. E. Piszel, C. E. Hayes, R. T. Baker, and W. D. Jones, “Highly Selective Formation of *n* -Butanol from Ethanol through the Guerbet Process: A Tandem Catalytic Approach,” *J Am Chem Soc*, vol. 137, no. 45, pp. 14264–14267, Nov. 2015, doi: 10.1021/jacs.5b10257.

[50] J. B. Heywood, *Internal Combustion Engine Fundamentals*. McGraw-Hill Education, 2018. Accessed: May 28, 2023. [Online]. Available: https://www.accessengineeringlibrary.com/content/book/9781260116106

List of Publication

International Conference

1. Deepak Kumar, Naveen Kumar, Rajiv Chaudhary, 2023, Use of Butanol, Petanol & Diesel in a Compression Ignition Engine: A Review. Proceedings of 4th International conference on Computational & Experimental methods in Mechanical Engineering (ICCEMME-2023).