EXPERIMENTAL & THERMODYNAMIC ANALYSIS OF CI ENGINE USING DIESEL-BASED BIOFUEL BLENDS

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By

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(Saket Kumar)

CANDIDATE’S DECLARATION

I, Saket Kumar, hereby declare that the thesis titled “**Experimental & Thermodynamic Analysis of CI Engine Using Diesel-Based Biofuel Blends**” which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Doctor of Philosophy, is original work carried out as a doctoral student and, to the best of my knowledge, it contains no material previously published or written by another person. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi **SAKET KUMAR**

CERTIFICATE

This is to Certify that **Saket Kumar** **(Roll No. 2K18/PHDME/501)** has carried out their research work presented in this thesis entitled **"Experimental & Thermodynamic Analysis of CI Engine Using Diesel-Based Biofuel Blends"** for the award of **Doctor of Philosophy** from Delhi Technological University, New Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or anybody else from this or any other University/Institution.

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ABSTRACT

The need for alternative and viable energy sources for the automotive industry is increasing due to the fast depletion of fossil fuel reserves. In the present scenario fluctuating petroleum prices, inconsistent supply, global politics, conflicts of oil-producing countries sky-rocketing energy demands, lacking oil reserves make an energy-intensive country like India, vulnerable to energy security. Rapid industrialization has significantly increased the world's energy usage. It has been visualized that petroleum-reserves will be scanty, and levels of pollution and global warming will be ample. One can solve these problems by using cleaner and renewable energy sources. For a few years, researchers across the world found Biodiesel as a favourable potential energy source to fulfil its energy needs due to its availability, renewable nature, low toxicity and lesser polluting nature. There are various sources of biofuel identified by the scientists and researchers so far, which include edible oil, non-edible oil, animal fats, microbial feedstocks, waste cooking oil, etc. making biodiesel viable for use and economical for production is the very next challenge for researchers. This doctoral thesis emphasizes on various selection criteria e.g. physicochemical properties, structural composition, environmental aspects, economic aspects etc. to choose better alternative out of the available biofuel resources.

Biodiesel can be easily prepared by renewable feed stocks. It is biodegradable and non-toxic as well as it can be used in pure state or by blending with diesel in a diesel engine without any major engine modifications. In this study, biodiesel is produced from tallow oil and blended in different ratios (10%, 20% and 30% abbreviated as B10, B20 and B30 respectively) with diesel and used as an engine fuel to compare combustion and performance characteristics e.g. in-cylinder pressure, rate of pressure rise, mean gas temperature, heat release rate, brake power, specific fuel consumption, brake thermal efficiency and torque. The experimental results showed that engine performance parameters support the use of biodiesel and its blends as fuel as the difference between maximum brake power values of diesel and biodiesel blends (B30) is 1.7% which is un-

noticeable, considering its other benefits. The similar results obtained for other characteristics. However, specific fuel consumption was higher in the case of biodiesel blends because of its lower heating value relative to diesel. Considering the fact that animal fat is voluminous by-product of meat Industry and it has limited use otherwise, the present investigation illustrates that biodiesel from animal fat can be used with efficacy without modifications in engine design.

Biodiesel has been accepted as an alternate fuel to power engines. Biodiesel, prepared by transesterification of tallow as a feedstock, is used to fuel a compression ignition (CI) engine. An Exergy-energy analysis is compared with baseline diesel at various engine design variables. Brake-specific fuel consumption (BSFC), fuel energy, thermal efficiency, heat loss, energetic efficiencies, and exergy destruction through exhaust gases were determined for a single cylinder, direct injection, variable compression ratio (VCR) CI engine. Data analysis provides optimal operating conditions for the efficient combustion of B20 blend fuel. Optimal performance was obtained at a compression ratio of 17.5 and injection pressure of 210 bar, with energy efficiency observed as 31.69% and the maximum efficiency observed for diesel was 32.67%. Exergetic efficiency values were 24.97% and 26.37%, respectively. Based on the data, it is proposed that B20 tallow-based biodiesel can be used as an efficient and sustainable fuel.

LIST OF PUBLICATIONS

Internation Journal:

List of Publications Based on the Research (present) work

1. Kumar, Saket, and Raghvendra Gautam. "Energy and exergy assessment of diesel-tallow biodiesel blend in compression ignition engine for engine design variables." *Sustainable Energy Technologies and Assessments* 57 (2023): 103305.
2. Kumar, Saket, and Raghvendra Gautam. "Prospects of Factor Affecting Biodiesel Selection Strategies Based on Various Aspects: An Indian Perspective." *Journal of Engineering Research (2307-1877)* (2022).
3. Gautam, Raghvendra, and Saket Kumar. "Performance and combustion analysis of diesel and tallow biodiesel in CI engine." *Energy reports* 6 (2020): 2785-2793.
4. Kumar, Saket, Prem Shanker Yadav, Raghvendra Gautam, and Manish Kumar. "Multi-aspect assessment and multi-objective optimization of preheated tallow biodiesel-diesel blend as alternate fuel in CI engine", Environmental Progress & Sustainable Energy. Manuscript ID: EP-24-015. (Under review-R1 Submitted).

International Conferences:

1. Research article presented entitled "One dimensional modelling and simulation of injection parameters on the combustion, knocking, and emissions behaviour for biofuel" for conference "ICARI-2022, Delhi" on 6-7th March 2022.
2. Research article presented with Paper ID: ICERTSD 2023-132 in ICERTSD 2023 on 27th – 28th April, 2023 on the topic "Assessing Exergetic and Sustainability Parameters of Tallow Biodiesel-fueled Diesel Engine.

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NOMENCLATURE

CI	Compression Ignition
CO_2	Carbon Dioxide
CO	Carbon Monoxide
HC	Hydrocarbon
NOx	Oxides of Nitrogen
PM	Particulate Matter
SO_2	Sulphur Dioxide
mb/d	Million barrel per day
IC	Internal Combustion
EVs	Electric Vehicles
GHG	Green House Gas
CH_4	Methane
BS	Bharat Stage
g/km	Gram Per Kilometer
WCO	Waste Cooking Oil
FFA	Free Fatty Acid
IMEP	Indicated Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
MMT	Million Metric Ton
ml	Milli Liter
gm	Gram
Mol. wt	Molecular Weight
KJ/Kg	Kilo Jule Per Kilogram
CN	Cetane Number
TCD	Thermal Conductivity Detector
hrs	Hours
Hz	Hertz
ms	Milli Second
µm	Micrometer
KW	Kilo Watt
rpm	Revolution Per Minute
FAME	Fatty Acid Methyl Ester
T	Temperature
ΔG	Gibbs Free Energy
ΔH	Enthalpy
ΔS	Entropy
M	Molecular Weight
ρ_l	Liquid Density
ρ_v	Vapor Density

ρ_g	Gas Density
B100	Biodiesel (100%)
B20	Diesel (80%)+Biodiesel(20%)
D	Diesel
CA	Crank Angle
P_{inj}	Injection Pressure
P_{amb}	Ambient Pressure
mN/m	Milli Newton per Meter
O_2	Oxygen
HRR	Heat Release Rate
CN	Cetane Number
ID	Ignition Delay
Wt%	Percentage of Weight
KOH	Potassium Hydroxide
PTSA	P-toluenesulfonic Acid
UBHC	Unburnt Hydrocarbon
GC	Gas Chromatography
hp	Horse Power
mg	Milli Gram

CHAPTER 1

INTRODUCTION

Overview

The current chapter is the first, which dedicated for energy scenario of India and the World and elaborates it with reference to petroleum economy. This chapter includes background information about the alternative fuels, its uses, various feedstocks available for use in CI engine combustion. Then the motivation behind performing this doctoral research work will be summarized. Lastly, this chapter ends with the outline of the thesis.

1.1 Energy Scenario and Petroleum Economy

Energy is a critical aspect for maintaining high standard of living along with maintaining economic progress. Energy demand is growing throughout the world due to a combination of factors, including population growth, economic development, urbanization, changes in energy consumption patterns, and others as discussed below:

- The world's population continues to grow, and more people require access to energy for various aspects of their daily lives, such as cooking, heating, cooling, and transportation.
- As countries and regions experience economic growth and development, there is an increased demand for energy to power industries, infrastructure, and services.
- Industrialization and urbanization drive up energy consumption. Urbanization is on the rise, with more people moving to cities.

- Technological advancements have led to the proliferation of energy-consuming devices, from computers to electric vehicles and smart homes.
- Growing car ownership and an increase in freight and passenger transportation contribute to rising energy demands, particularly in the transportation sector.
- Increased global trade and supply chain logistics demand energy for shipping, aviation, and long-distance transportation.
- The demand for heating and cooling, driven by temperature extremes and increased urbanization, is growing, requiring energy for heating systems.

Fossil fuels, including coal, oil, and natural gas, have been the dominant sources of energy for over a century. The three fossil fuel categories are now projected to reach a peak by 2030, as the energy system is changing because of low-emissions electricity and fuels meet an increasing share of the world's rising energy needs, and as energy efficiency improvements help to moderate those needs. As shown in Fig. 1.1, total demand for primary energy consumption declines from the mid-2020s by an average of 3 exajoules (EJ) per year to 2050 in the STEPS, and the peak in energy-related CO_2 emissions in the STEPS is brought forward to the mid-2020s [1].

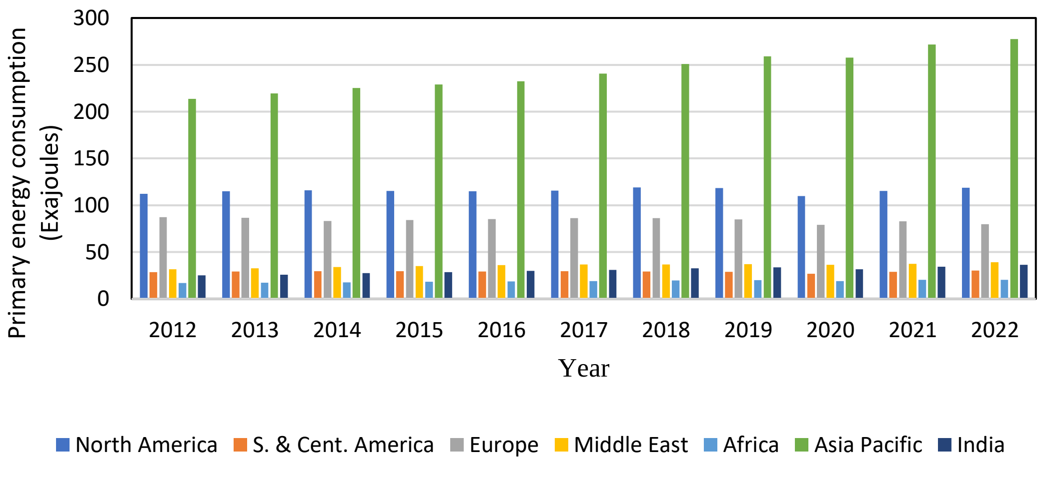


Fig. 1.1 Primary energy consumption of India and the world

The infrastructure, technology, and knowledge surrounding their extraction, production, and use have deep historical roots, making them the default energy sources. The majority of modern societies energy demands are today met by energy sources based on coal, petroleum, and natural gas. Since, nineteenth century, fossil fuels have been critical in meeting global energy demand. Fossil fuels have a high energy density, which means they contain a significant amount of energy per unit of volume or weight. This makes them highly efficient for many applications. Fossil fuels have historically been relatively affordable energy sources, making them attractive for both consumers and industries. It has been extensively used in transportation, agriculture and industrial sectors. The global transportation sector heavily relies on fossil fuels, particularly petroleum-based fuels like gasoline and diesel. These are highly portable and energy-dense, making them ideal for use in vehicles. The existing energy infrastructure, including power plants, pipelines, and refineries, is designed to work with fossil fuels. Transitioning away from them can require extensive changes and investments. While alternative energy technologies exist, such as renewable energy sources and electric vehicles, they may not yet offer the same level of convenience, affordability, and scalability as fossil fuels. The development and deployment of alternative energy technologies face challenges in terms of energy storage, intermittency (in the case of renewables), and infrastructure development. There can be resistance to change, particularly when transitioning away from established systems and industries. This resistance can come from various stakeholders, including workers, companies, and communities heavily reliant on fossil fuels. It can be inferred that people are accustomed to the convenience of fossil fuel-based technologies. Fossil fuels are relatively easy to store, transport, and use, which has contributed to their widespread adoption. Some countries have abundant fossil fuel resources, while other countries are devoid of them, which leads to geopolitical imbalance with trade and price monopoly. Supplies of fossil fuels across the world face a number of challenges due to the uneven distribution of resources. The necessity for transportation of oil and oil derivatives globally are major challenges. The aforementioned concerns will deteriorate in the future because of the fast depletion of major oil reserves in the coming years and the irreversible growth of both global population and energy demand.

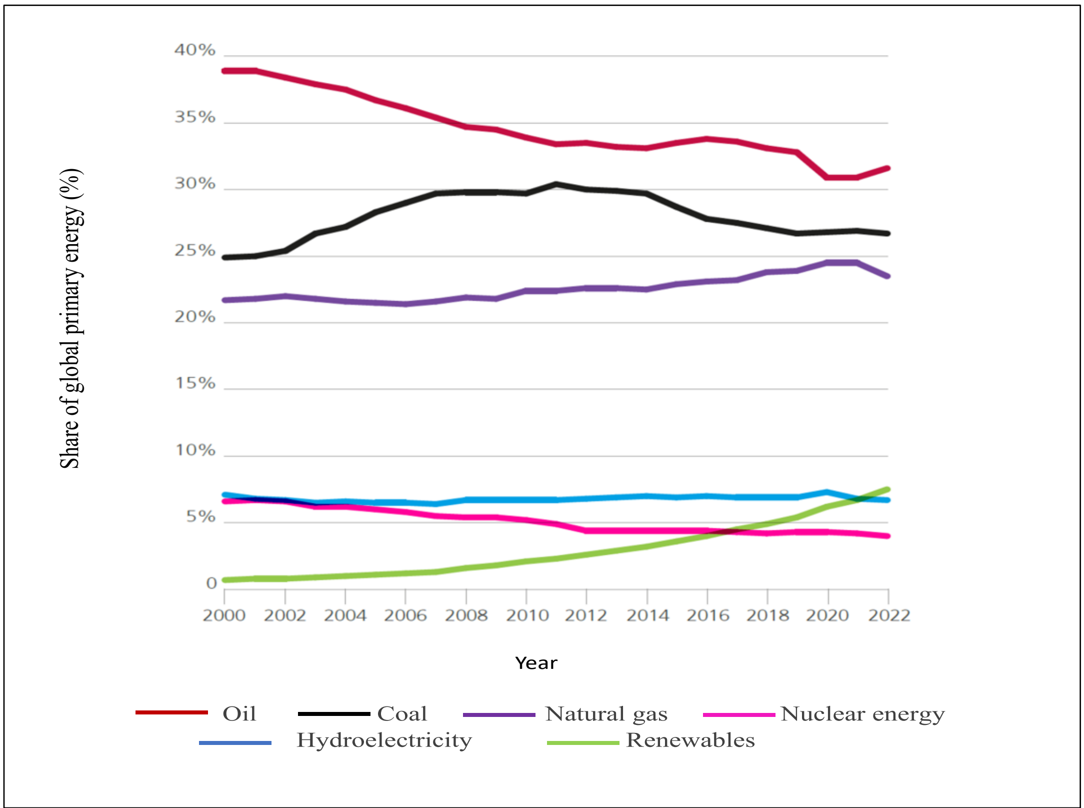


Fig. 1.2 Share of global primary energy consumption

The world energy forum in their recent report predicted that fossil fuel reserves will be depleted by 2070, if consumed at this rate of consumption. However, if consumption continues at a 3% annual increase, it will be depleted in less than 30 years [2]. Fossil fuel reserves are finite and diminishing, leading to concerns about energy security. Sustainable energy seeks to address these resource scarcity challenges by harnessing renewable and abundant energy sources. So, transitioning away from fossil fuels and toward low-carbon or carbon-neutral energy sources to combat climate change. The prices of petroleum products in international markets are volatile and hence they are not sustainable. In addition, it is thought that burning fossil fuels is to blame for environmental issues like smog, acid rain, and climate change. CO2, NOx, volatile organic compounds (VOC), and hydrocarbons (HC) are mostly produced by fossil fuels [3].

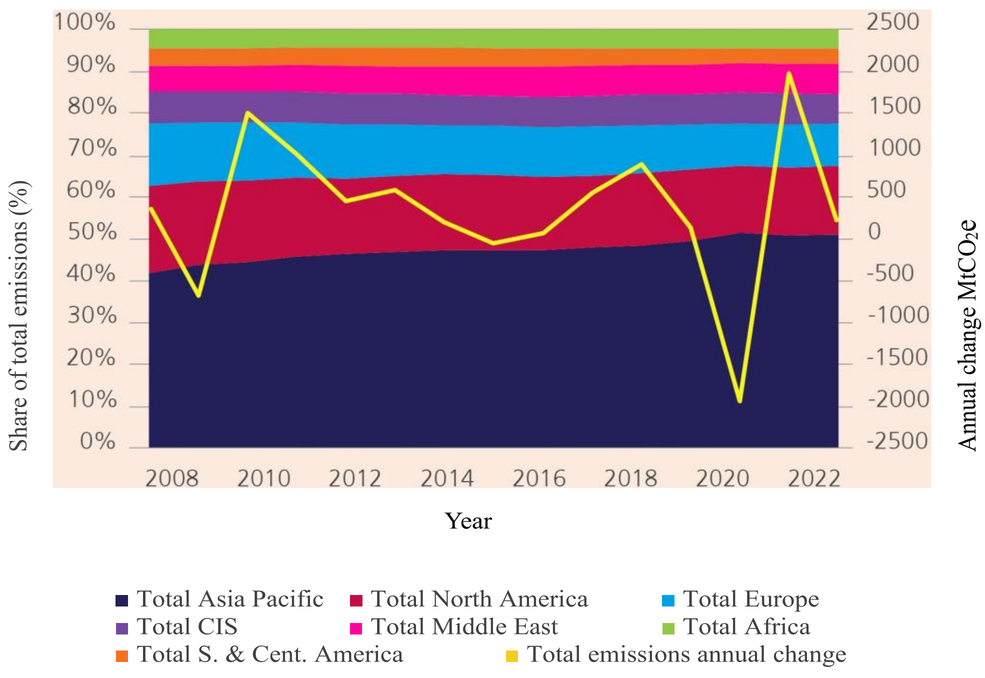


Fig. 1.3 Share of total emissions and carbon emissions

In 2030, it is expected that CO_2 would increase to 40,000 billion kg. Globally, the accumulation of CO_2 and the other greenhouse gases a result of the burning of fossil fuels for industry and transportation is having a significant impact on ecosystem degradation due to the presence of contaminants derived from hydrocarbons and global climate changes due to the enhancement of the greenhouse effect [3]. The negative environmental impacts of fossil fuels, including air and water pollution, habitat destruction, and oil spills, underscore the need for cleaner, more environmentally responsible energy solutions. Up to a million species might go extinct and hundreds of millions of people could face habitat loss if the average global temperature rises by more than 2 °C [4]. The world is facing a climate crisis, with rising global temperatures, extreme weather events, and other environmental challenges. Transitioning to sustainable energy sources is crucial to reducing greenhouse gas emissions and mitigating the effects of climate change.

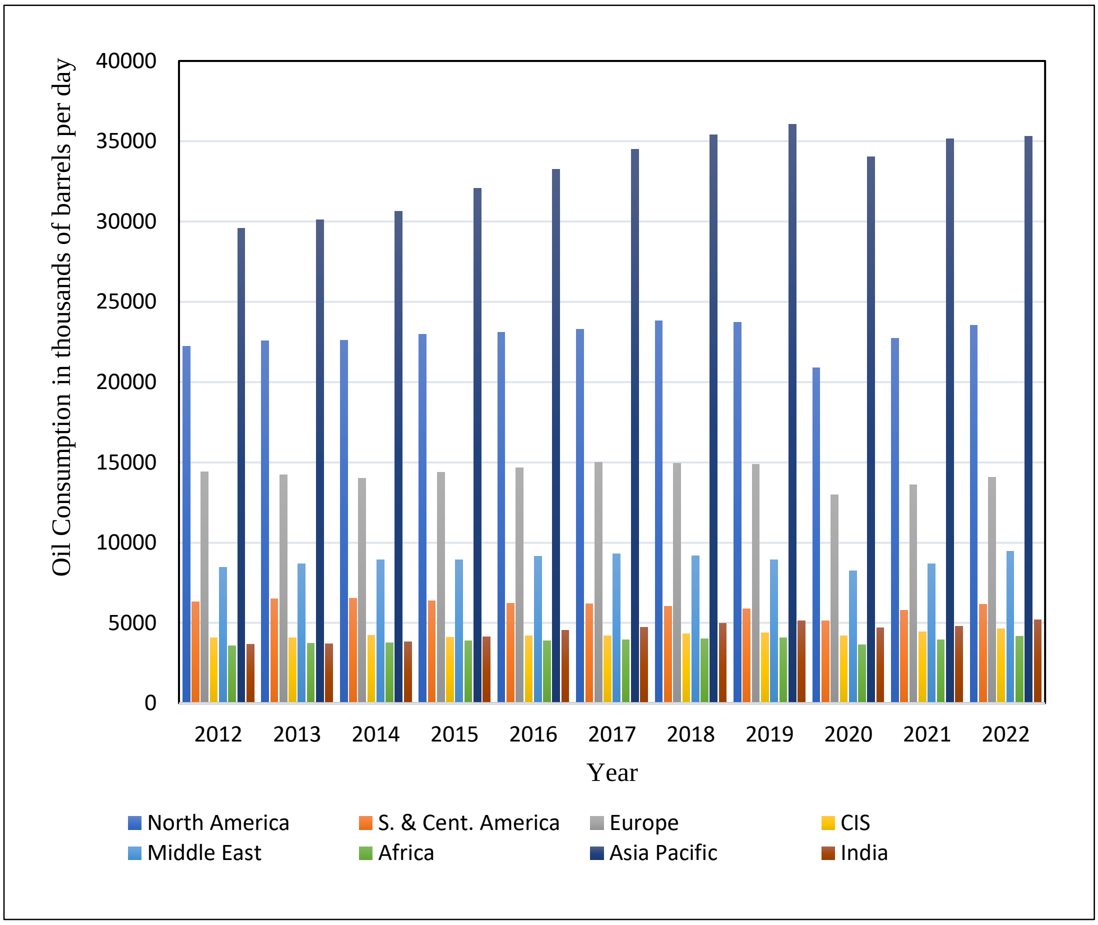


Fig. 1.4 Oil consumption (India and the world)

To address the growing global energy demand in a sustainable manner and mitigate its impact on climate change and resource depletion, there is a need to transition to cleaner and more efficient energy sources, improve energy conservation, enhance energy efficiency, and implement policies and practices that promote responsible energy consumption. This transition is critical for ensuring access to reliable energy while minimizing environmental and social impacts. While the world is gradually shifting towards cleaner and more sustainable energy sources due to environmental concerns and the need to address climate change, the deeply entrenched dependency on fossil fuels presents challenges that require careful planning, investment, and policy support to overcome. Sustainable energy management involves conserving finite energy resources, such as fossil fuels, and promoting the use of abundant, renewable resources like sunlight, wind, and biomass. The depletion of fossil fuel supplies, combined with the realization that climate change is being exacerbated by rising CO2 emissions, has fuelled interest in promoting biofuels as one of the major renewable energy sources. Sustainable biofuel production is an important instrument for combating climate change, strengthening local economies, particularly in less developed parts of the world, and improving energy security for all [5]. Sustainable energy practices aim to reduce negative environmental impacts, including the emission of greenhouse gases, pollution, and habitat destruction. Sustainable energy solutions are economically viable and promote long-term economic growth. They should be cost-effective and not impose excessive financial burdens on individuals or societies. Sustainable energy encourages innovation in technologies and practices, fostering the development of cleaner, more efficient energy solutions.

1.2 Renewable alternatives to petroleum

The United Nations Climate Change Conference, 2009, also known as the Copenhagen summit, highlighted the benefits of using sustainable bioenergy feed-stocks to produce renewable and clean fuels that can lower greenhouse gas emissions (GHGs), increase food security, and lessen poverty worldwide. A reduction in green-house gas emissions of 40 million tonnes can be expected as a result of the global biodiesel production of 17 billion litres. The total decrease in green house gas emis-sions from biofuels is 123.5 million tonnes, or nearly 57%, less than what would have been produced and released had similar amounts of petroleum fuels been produced and used instead[6].

1.2.1 Hydrogen

The widespread adoption of hydrogen as an alternative fuel for IC engines have been carried out by technological advancements. There are various methods to use hydrogen as a fuel substitute for IC engines, but the two most common are using hydrogen fuel cell or burning hydrogen directly in IC engines. Hydrogen can be used in Hydrogen is a clean fuel, as it produces zero emissions when used in fuel cells. The only by-products of this process are water vapor, and heat; making fuel cells a clean and efficient energy sources. It has a high energy density by weight, making it suitable for use in transport vehicles. Hydrogen fuel cells generate electricity, which are often used to power vehicles including cars, buses, trucks, etc. It can be used as a supple-mentary fuel in hybrid vehicles e.g. to act as supplementary power source to extend the range of an electric vehicle. Existing IC engines can be modified to use hydrogen, though some adjustments are needed due to hydrogen's different combustion charac-teristics [7]. Hydrogen, when blended with natural gas are used in existing natural gas engines. This approach allows for a step-by-step transition for increasing percentages of hydrogen over time.

1.2.2 Bioethanol

India is ramping up output to meet its 20% ethanol blending target by 2025, supported by guaranteed pricing and incentives for new ethanol facilities. World ethanol production was 1,836 thousand barrels per day in 2021 and expected to reach to 2,061 thousand barrels per day by 2026, with United States and Brazil to be two largest producer and India produced 80 thousand barrels per day in 2022 [8]. Bioethanol is produced by fermenting sugars of different biomass rich in sugars such as corn, sugar beets, and sugarcane which are easily converted into ethyl alcohol to use in internal combustion engines for combustion [9]. Three phases are involved in the manufacture of bioethanol: Compound sugars are first hydrolyzed to produce glucose. Then, the glucose fermentation process continues in a second stage, producing ethanol and carbon anhydride. In the third phase, diluted alcohol is distillated to produce absolute ethanol by a thermochemical process.

1.2.3 Biofuel

Using vegetable oils as the feedstock, the transesterification of fatty acids and alcohols give mono-alkyl fatty acid esters (FAAE) [10]. Esters obtained from methanol are known as fatty acids methyl esters (FAME), while fatty acid ethyl esters (FAEE) if esters obtained from ethanol. The fundamental benefit of using biodiesel as a fuel is that it maintains the CO_2 equilibrium because it is made from renewable biological resources. Due to its high biodegradability and low toxicity, biodiesel may easily replace diesel fuel in a variety of applications for internal combustion engines, without requiring significant adjustments [11]. Additionally, a slight decline in performance has been noted, and nearly no emissions of sulphates, aromatic compounds, or other chemicals that are harmful to the environment are produced. When the entire life cycle is considered (including farming, oil production, and biodiesel conversion), the carbon dioxide (CO_2) emissions are quite low, and it appears to have a major positive impact on rural economic potential [12]. There is a significant chance that production and application of biodiesel has been found throughout the world. The production of biodiesel rose manifolds from 952 thousand barrels per day in 2021 to 1042 thousand barrel per day in 2022 and expected to reach to 1,404 thousand barrels per day in 2027 with United States and Brazil are two top producers [8]. Additionally, it offers several environmental advantages, including minimal emissions of CO, sulphur, aromatic hydrocarbons, and particulate matters. It is biodegradable and non-toxic. Also, it has low flammability and is safe to handle because of its high flash point. Direct usage of conventional diesel engines with blends of biodiesel and conventional diesel.

1.2.4 Drop-in fuels (Green gasoline)

Fuels made from lignocellulosic feedstocks e.g. agriculture residues such as rice and wheat straw, corn cobs and stover, and woody biomass), non-food crops such as algae, or industrial waste and residue streams that have low CO2 emissions or high GHG reduction and do not compete with food crops for land use are referred to as advanced biofuels e.g. second generation ethanol, drop-in fuels, algae based 3G biofuels, bio-CNG, biomethanol, Di Methyl Ether (DME) [13].The fuel made from vegetable oils, animal fats, agriculture residues, biomass, wastes from industries or municipal etc. that satisfies the same ASTM D4814 specifications for petroleum gasoline for use in automobiles without requiring engine system modifications. It can be produced by variety of methods which include (a) Traditional hydrotreating (b) biological sugar upgrading (c) catalytic conversions of sugars (d) gasification (e) pyrolysis (f) hydrothermal processing.

1.2.5 Naural Gas (CNG and LNG):

Existing gasoline or diesel engines can be converted to operate on natural gas by modifying the fuel delivery systems and making adjustments to accommodate the different combustion characteristics. Natural gas can be used in combination with hydrogen to enhance combustion characteristics, lower emissions and improved combustion efficiency. Combustion of natural gas produces fewer pollutants, such as carbon monoxide, nitrogen oxides, and particulate matter, compared to traditional fuels. As natural gas is abundant and widely available, the dependence on petroleum fuels can be avoided. Natural gas provides a cleaner-burning option compared to traditional gasoline or diesel through various ways:

Compressed Natural Gas (CNG): Natural gas is compressed to high pressure (typically between 3000 to 6000 psi) to become CNG, which is stored in high-pressure cylinders on vehicles. CNG is injected into the engine's combustion chamber using a fuel injection system designed for gaseous fuels, where it mixes with air and is ignited by a spark plug, similar to gasoline combustion.

Liquefied Natural Gas (LNG): Natural gas is cooled to extremely low temperature to convert it into a liquid form (LNG) for easier storage and transportation.

It is stored in cryogenic tanks on the vehicle. For combustion in engine, it is injected in gaseous state after vaporization.

1.2.6 Liquified Petroleum Gas (LPG):

Propane is the primary component of LPG, with some amount of butane and other gases. It is stored in high pressure tanks as liquid. For combustion in engine, it is injected as vapor. Fuel injection systems of the vehicle may have carburettor or a dedicated fuel injection system for better control of fuel delivery. LPG combustion generally results in lower emissions of carbon monoxide, nitrogen oxides, and particulate matter compared to gasoline. It contributes to reduced greenhouse gas emissions due to lower carbon content. It also offers a cost benefit as it is less expensive than gasoline. Due to unavailability of refueling infrastructure and lower energy density, overall driving range of a vehicle is limited.

1.2.7 Ammonia

Ammonia offers a potential alternative to petroleum fuels for reducing greenhouse gas emissions. The Ammonia can be used as a carrier for hydrogen or in other words, hydrogen can be extracted from ammonia which can be used as a fuel in internal combustion engines [14]. Ammonia itself can be used as fuel in internal combustion engines as similar to conventional liquid fuels. The ammonia can be used in dual-fuel engines in conjunction with another fuel like diesel or natural gas. Existing IC engine requires modification in fuel injection system, or in combustion chamber design to accommodate ammonia as a fuel due to difference in combustion characteristics. Though combustion of ammonia results in low carbon emissions but high NOx emissions remains a challenge. Also, ammonia is toxic and requires careful handling and storage.

1.3 Potential alternative fuel for CI engines

1.3.1 Vegetable oils

Vegetable oils can be edible oil and non-edible oils, which are composed of triglycerides. Examples of edible oil seed crops include palm, soybean, sunflower, canola, and rice bran; whereas non-edible oil seed crops include rubber, jatropha, mahua, karanja, and neem. Vegetable oils have gained in popularity over the past three decades as an alternative to petroleum-based fuels since they are environmentally beneficial, naturally renewable, and generated from renewable resources.

1.3.2 Biodiesel

The term “biodiesel” generally refers to the methyl, ethyl, or butyl ester produced from vegetable oils, animal fats, or algae [15]. It is a fuel made from mono-alkaline esters of long-chain fatty acids that are synthesized from algae, animal fats, and vegetable oils (both edible and non-edible). Vegetable oils are better source for synthesizing biodiesel as compared to animal fats and algae.

1.3.3 Bioethanol

Ethanol derived from biomass such as starch containing materials such as cassava, potato, starch etc.; sugar containing materials, such as sugarcane, sweet sorghum, sugar beet; cellulosic materials such as agriculture and forestry residues along with industrial waste. An oxygenated fuel called ethanol is created by fermenting biological renewable sources like molasses, sugar cane, or starch etc. Ethanol is one of the potential fuels for diesel replacement in CI engines due to the reduced environmental damage it causes. In the USA, ethanol was first proposed as a fuel for cars in the 1930s, but it wasn't until 1970 that it became widely accepted. The demand of using ethanol for blending with diesel has arisen as a result of the rapidly rising ethanol production and its lower cost in comparison to fossil fuel in nations like Brazil. In India, sugarcane molasses is used to make ethanol, which is then blended with gasoline. Ethanol Blending Program (EBP) launched in 2003 in India across a number of states, the Government of India mandated the use 5% ethanol blending in gasoline from year 2020 and ethanol blending target of 10% from 2022 onwards, which is to progressively increase to 20% by ESY 2029-30 [16]. In keeping with this, on December 24, 2009, the Indian government approved the National Policy on Biofuels to encourage the production of energy using renewable energy sources as an alternative fuel to transport petroleum fuels, and had proposed an indicative target of replacing 20% of petroleum fuel consumption with biofuels [17]. The National Policy on Biofuel (NPB) – 2018 of Indian government provides an indicative target of 20% ethanol blending in petrol by 2030.

Different methods can be used to combine ethanol with diesel. Blending and fumigation are the two most used techniques. In the blending procedure, diesel and ethanol are combined before being injected into the cylinder. Additionally, chemicals are needed to stabilize the miscibility of combining ethanol and diesel, which limits the amount of blending with diesel. Simply said, ethanol fumigation is the process of injecting, carburetting, or spraying ethanol into the intake air upstream of the manifold [18]. This technique of introduction has the advantage of enhancing air utilization by supplying a percentage of the total fuel supply premixed with the air intake air. The ethanol contains about 35% oxygen, makes it a good choice of for use as an automotive fuel except the fact that its calorific value is about 40% lower than gasoline. Ethanol absorbs moisture rapidly, due to which alcohol is corrosive in nature and can harm metallic components of engine. However, ethanol blending up to 10% do not pose such problems. Also, Blending above 20% present similar other challenges e.g. (i) higher aldehyde emissions, (ii) starting issues due to higher latent heat of vaporization, (iii) high vapour pressure causes higher evaporation losses, (iv) a need for a large fuel tank due to lower calorific value.

1.3.4 Diethyl ether

Diethyl ether (DEE) can be obtained from waste and renewable feedstock. It is an inert liquid that is very volatile and flammable. DEE is regarded as a high-quality, low-emission diesel engine fuel. Its benefits include a high oxygen content, low auto ignition temperature, and a very high cetane number [19]. It mixes well with diesel fuel and 5% blending with diesel was found optimum for use in diesel engine as it offers drastically reduced CO, HC, NO, and PM emissions when utilized as a diesel engine fuel. The following drawbacks of DEE put the limitation in its wide use as diesel engine fuel (i) low auto ignition temperature, wide range of flammability limits, propensity for peroxidation during storage, harmful effects on human health. Reports suggested that mixing DEE with diesel reduces emissions and enhances engine performance.

1.4 Motivation of this research

The search for new alternative fuels is imperative to address environmental, economic, and energy security concerns. It offers the potential to reduce greenhouse gas emissions, enhance energy security, create economic opportunities, and drive technological innovation, ultimately contributing to a more sustainable and resilient energy future. motivation to find new alternative fuels is fueled by a combination of environmental concerns, economic incentives, technological opportunities, and ethical responsibilities. It is through sustained motivation and concerted efforts that researchers and society can work together to transition to cleaner, more sustainable energy sources. Researchers should **work to find new alternative fuels** for several compelling reasons:

1. **Environmental Concerns:** Motivation comes from a desire to combat climate change and reduce environmental damage. The burning of fossil fuels is a major contributor to greenhouse gas emissions and air pollution [20]. These emissions contribute to climate change and air pollution. Finding cleaner alternative fuels is crucial for mitigating these impacts and preserving the environment for future generations. Alternative fuels, such as biofuels, hydrogen, and electric power, can significantly reduce or even eliminate these harmful emissions, helping to mitigate the effects of climate change and improve air quality.
2. **Energy Security:** Many countries depend on imported oil and gas, which can make them vulnerable to supply disruptions and price fluctuations. Oil prices can be highly volatile, impacting the global economy and contributing to uncertainty in various sectors, including transportation and manufacturing. Many oil-producing regions are politically unstable, and conflicts over oil resources can lead to global tensions and supply disruptions. By developing alternative fuels from domestic resources, nations can enhance their energy security and reduce their reliance on geopolitically unstable regions.

3. **Resource Depletion:** Fossil fuels are finite resources, and their extraction can lead to resource depletion and environmental damage, such as oil spills and habitat destruction. Alternative fuels, including those derived from renewable sources like wind, solar, and biomass, are more sustainable and do not deplete finite resources [21].
4. **Diversification of Energy Sources:** Relying on a single source of energy, such as oil, can lead to vulnerability in the event of supply disruptions or price shocks. Developing and using a variety of alternative fuels allows for a more diverse and resilient energy portfolio.
5. **Economic Benefits:** The development and production of alternative fuels can create new industries and job opportunities, boosting economic growth. In addition, these fuels can often be produced locally, reducing the need for imports and stimulating regional economic development.
6. **Technological Innovation:** Research into alternative fuels drives technological innovation. This innovation can lead to breakthroughs in energy efficiency, transportation, and other sectors, benefiting society in various ways.
7. **Energy Efficiency:** Some alternative fuels, such as hydrogen and electricity, are more energy-efficient than traditional fossil fuels. This increased efficiency can lead to cost savings and reduce the overall environmental impact of energy production and consumption.
8. **Reduced Greenhouse Gas Emissions:** Alternative fuels can have significantly lower greenhouse gas emissions compared to fossil fuels. This is crucial

for meeting emissions reduction targets outlined in international agreements like the Paris Agreement and addressing global climate change [22].

9. **Transportation Sector:** The transportation sector is a major contributor to greenhouse gas emissions. Finding alternative fuels for vehicles, such as electric vehicles and hydrogen-powered vehicles, is essential for reducing the sector's environmental impact.
10. **Public Health:** Traditional fuels release pollutants that have adverse health effects, including respiratory problems and heart disease. Transitioning to cleaner alternative fuels can improve public health by reducing exposure to harmful pollutants.

Numerous efforts have been made to decrease the dependence on conventional sources of energy. International agreements, such as the Paris Agreement, set targets for reducing greenhouse gas emissions and transitioning to sustainable energy systems. Many countries are working to meet these commitments. Motivation to find new alternative fuels is essential for driving progress in this critical field of research and development. Various efforts implied to increase the effectiveness of the currently available biofuels. However, most of these alternative sources of energy still have lot of difficulties that have not been resolved. Moreover, a significant driving force behind this research is the dependence on automobile for transportation, especially which are running on petroleum. The most frequent shortcomings of the present methods are high energy demands, restrictions on dealing with a large number of design variables, sensitivity to initial design points, and installation difficulties. Improving the stability of combustion difficulties in biofueled engine is one of the key goals of this research.

Establishing biodiesel as potential and sustainable fuel for CI engine is one of the principal motivations of this thesis.

1.5 Thesis outline

This thesis is organized in five chapters and two appendix sections.

Chapter 1: Introduction

Chapter 1 imparts the detail overview of current research. The current chapter is the first, which dedicated for energy scenario and elaborates the motivation behind performing this doctoral research work. Further, the subsequent section explains the importance of alternative fuels particularly the current status of biodiesel and availability in India. Then, it continued with problems associated with alternative fuel during application. At the end of the chapter, motivation behind this doctoral research is concluded.

Chapter 2: Literature Review

Chapter 2 incorporates the brief literature survey that provides a summary of selection of biodiesel, physico-chemical properties, thermodynamic analysis, quality of biodiesel etc. The existing literature in the broad area of alternative fuel will be reviewed in chapter 2. The research gap will be found out from the exhaustive research work. A survey of the most pertinent scientific literature from selection of fuel to their thermodynamic analysis will be presented in section wise in this chapter. The role of combustion and performance characteristics of diesel engine as well as exergy-energy analysis of alternative fuel in the past study was concluded briefly.

Chapter 3 Fuel for Combustion

Chapter 3 includes the detail study of fuel. It starts with basis of selection of biodiesel and then describes the effect of altering fuel properties. It discusses the processes of production of biodiesel from selected feedstock. Then, physico-chemical properties of the fuel are obtained by following ASTM standards.

Chapter 4 Experimental Setup and Methodology

Chapter 4 discusses the processes to generate biodiesel from feedstock. Then, the methodology applied to measure the physico-chemical properties is explored in detail. Further, the system development to conduct engine trails has been described thoroughly. The thermodynamic study has been performed to analyze the complexity of energy-exergy evaluation by making control volume for engine setup. The corresponding appropriate model has applied to examine the energy exchange through different modes. Information on the sources of materials, methodologies adopted for finding different parameters were presented in this chapter. Mathematical equations used in evaluating different parameters and the setup model analysis were carried out in this chapter. Chapter three explains experimental setup and process parameters used to perform experimental work. The methodology required to accomplish the present work has also been discussed. It includes the basics of thermodynamic and equations used to evaluate exergy and energy values.

Chapter 5 Results and Discussion

Chapter 5 exhibits the comprehensive investigation on the results attained from the experimental work, characterization techniques and thermodynamic assessment utilized in the current study. Experimental results obtained were presented as tables and figures in this chapter. Detailed analysis of all the results were done in this chapter. This chapter covers the analysis of results obtained from the experimental and analytical work.

Chapter 6 Conclusions and Scope of Future Work

Chapter 6 This is the last chapter of thesis and that contains the summary, and relevant points is explored in the current research. The logical outcomes is drawn as per the figures and facts and also based on the formulated objectives. Further, the recommendation for future work has been explored, and finally the references as well as appendices associated with the current research work has been enumerated. Conclusions derived from obtained results and recommendations for future work were presented in this chapter.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses the previous work and state-of-the-art in the field of fuel combustion phenomena of biodiesel. The discovery of modern biodiesel fuel dates back to studies done in Belgium in the 1930s. However, the biodiesel business rose to prominence following the 9/11 terrorist attacks, which drove up oil costs. Hence, from the past 20 years, extensive researches have been done in this area. Biodiesel is the trade name of fatty acid methyl esters, which was made by converting vegetable oils into compounds called fatty acid alkyl esters. The significant works from the selection of biodiesel to energetic-exergetic study have been discussed in this chapter. The objectives of this doctoral thesis will be concluded from the research outcomes at the end of this chapter.

2.1 An overview of selection of biodiesel

The primary energy source used for automobiles are petroleum, and dependence on it has increased manifold in the last decade. The automobile industry is expanding at a faster rate than all others due to rise in economic activity and better way of communications. This impacted the diminution of petroleum reserves at much faster rate, which is limited and non-renewable. The shortage of petroleum-based fuel may be considered as a sustainable and attractive hot spot for elective fuel for the future [23]. However, biodiesel powers are being taken into account worldwide as a mixture part or an immediate substitute of petroleum in diesel engines [24]. As a result, biofuel is regarded as a potential alternative fuel source for high-powered diesel engines that run on non-marketable feedstock oil. Additionally, biodiesel have a remarkable potential to replace the conventional fuel. In addition, the shortage of regular petroleum derivatives, the growth of ignition sources that generated poisonous gases, ozone-depleting substances have caused climate pollution and raised global temperatures.

Research community are actively trying to search for different alternative for conventional fuel. The goal is to encourage the use of renewable energy sources and reduce the negative effects of exhaust polluting gases. According to earlier studies, using biofuel in an internal combustion engine will lessen the detrimental consequences on the well-being of the planet. Analysts are of the view that most biofuels have comparable physicochemical properties about their non-hazardous, non-harmful, recyclable, and no fuel attributes [25].

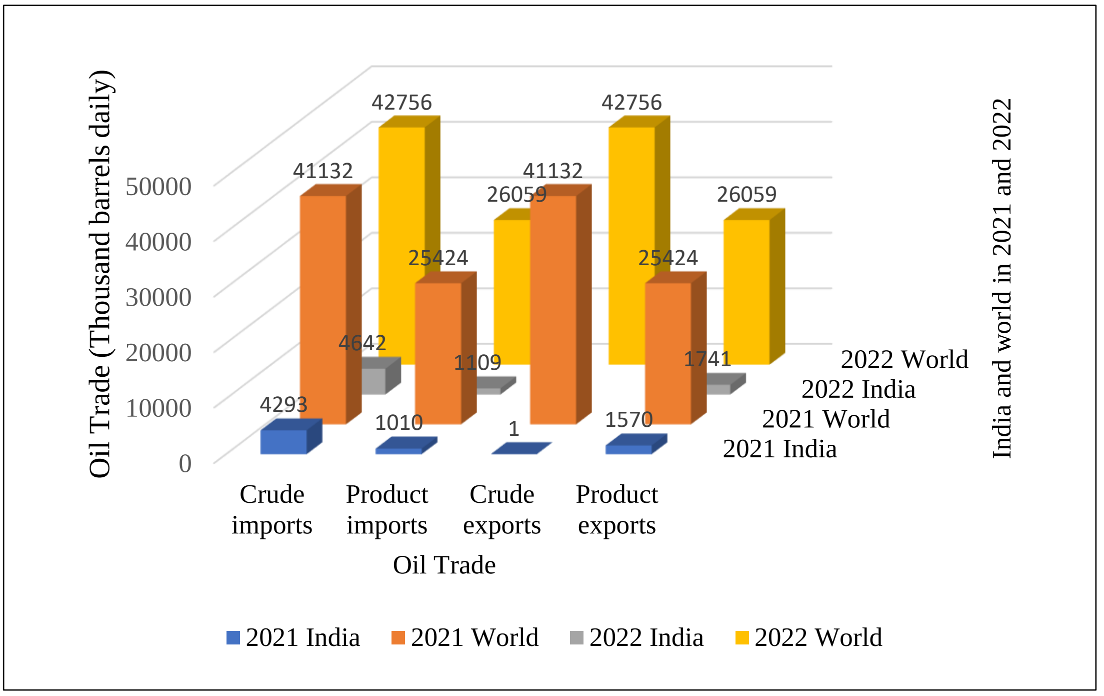


Fig. 2.1 Oil Trade in 2021 and 2022

2.1.1 Classification of Feedstocks for Biodiesel Production

Researchers are working to identify the finest feasible substitute feedstocks for the manufacturing of biofuels. However, picking a higher-quality feedstock at a reasonable price is essential for assuring low production costs for biodiesel. The production of biodiesel has two conditions that biofuel feedstock should satisfy i.e. a lower cost of production and a larger scale of production. It is a reality that the availability of biofuel feedstock is typically determined by a country's regional environment, geographic position, soil quality, and agriculture practices. Due to its potential as a replacement or supplement for conventional diesel, the production of biodiesel has attracted a lot of interest in recent decades. In several nations, biodiesel made from edible or non-edible oil seeds is now being used for fueling IC engines. Figure 1.2 represents the world's biggest biodiesel producers in 2015, by country (in billion litres) in the world. There are different feedstocks found for biodiesel production depending geographical locations. In India, some of these oils are use to make food like soybean oil, sunflower oil, Coconut oil, or palm oil; are also suitable to make biodiesel. Due to large population base, there is huge disparity in demand and supply of edible oils in India. Therefore, only non-edible oil seed plants can be taken into account for the production of biodiesel. Section 2.1.2 provides the details of different types of non-edible seed considered for biodiesel production, and the total planted area in various states of India. Variety of non-edible feedstocks e.g. Jatropha curcas, Rapeseed, Linseed, Pongamia pinnata, Madhuca Indica, Cotton seed are used for production of biodiesel. The highest oil content and biodiesel yield among the non-edible seeds produced in India are found in Jatropha curcas. In order to promote biodiesel production and replace diesel, particularly in transportation; the Ministry of New and Renewable Energy (MNRE) announced the "National Policy on Biofuels" programs in 2009, for which the Indian government has identified waste land where non-edible oil seed plants can be grown to enhance the production of biofuels.

Certain factors need to be considered while contrasting different feedstocks. Every feedstock should be given a thorough life-cycle review. These include: (1) greenhouse gas emissions; (2) the economic worth of feedstocks; (3) loss of diversity (4) the availability of land; (5) logistic expenses; (6) pesticide application; (7) farming practices; (8) soil degradation; (9) energy equivalent [26].

Previous studies have classified Algae as vegetable oils that cannot be consumed. On the other hand, only a few scholars, such as Moser (Moser 2011) have considered algae in a different category because of its high oil content and being non-edible oil.

2.1.2 Available Feedstocks for Biodiesel Production

Microalgae may be a viable and cost-effective source of biofuel [27]. Microalgae have a higher photosynthetic ability, biomass production, and growth rate than energy crops [28]. Though microalgae can replace diesel for engine use it was the same disadvantages as diesel fuel which include, lower volatility, higher viscosity, and unsaturated hydrocarbon chain operation [29].

WCO as a diesel fuel could be used and managed properly to solve this issue [30]. WCO is available in a variety of locations, mostly in homes and restaurants, and is an excellent alternative feedstock source. When compared to the cost of manufacturing crude oil, the usage of WCO significantly reduces the cost of creating biodiesel. These days, it has been shown that a significant quantity of waste lipids is produced by homes, food processing facilities, restaurants, and fast-food outlets. Reports state that in many nations, inappropriate WCO disposal leads to serious environmental problems [31]. This problem might be resolved by using and managing WCO as a diesel fuel [32]. The WCO's chemical and physical characteristics differ from those of fresh oils when it is fried and then reused.

Animal fats e.g. Tallow is an important source of feedstock that is used to make biodiesel. Tallow is a rendered form of animal fat that is high in triglycerides [33]. It may be stored in an airtight container to prevent oxidation for a long period and remains solid at room temperature. Its composition is made up of 32.28% and unsaturated fatty acids and 64.42% saturated fatty acids. Tallow is a great primary biodiesel feedstock because of its high amount of saturated fatty acids. It has been discovered that the methyl ester of animal fat offers a few benefits, such as a high cetane number, non-corrosion, safe, and renewable qualities [34]. While it has certain disadvantages, such as a greater pour point, viscosity, and flash point, it also has benefits like low water content, and most crucially, less free fatty acids (FFAs) [35]. The most efficient biodiesel feedstock has superior engine performance, better emission characteristics, and good combustion behavior when it has a higher oil content and a higher conversion rate.

A drought resistant tree, Moringa (Moringa oleifera), smaller in height grows swiftly. It originated in tropical and subtropical regions of South and Southeast Asia, and the world's largest producer of Moringa is India [33]. You may consume the leaves of the moringa plant as a vegetable, and the oil is mostly utilized in conventional herbal remedies. Despite having a high oil content, moringa seeds are only used sparingly since edible oil is becoming more and more popular. India is the world's leading producer of Moringa [36].

Tropical and subtropical climates are home to Jatropha plants. It is a drought-tolerant tree that grows to an average height of 5-7 metres and may be planted on bare ground. It yields upto eight tons of seeds annually per hectare of land. Of the fatty acids in the seed, around 77.4% are unsaturated and 22.6% are saturated. The non-edible oil category includes Jatropha (JBD) oil, which is quite prevalent and contains a high concentration of oleic and linoleic acids.

Plants in the mustard family (Brassicaceae) that grow up to 60 cm tall include rapeseed (Brassicanapus). On cold weather, it grows well on well-drained soils. The main reason this is grown is for the seeds. It's growing more widespread on practically every continent. Because natural rapeseed contains around 50% erucic acid, it is an inedible commodity. Canola oil is derived from a range of rapeseed plants. The percentage of rapeseed oil varies from 38 to 46 percent. The oil output from the beautiful leaf tree (Calophylluminophyllum) is the greatest (65%) of all the biodiesel feedstock available globally.

Temperate conditions are ideal for mustard plant growth. It might be yellow or blackish in appearance, with a diameter of 1-2 mm. Because of its unique flavor, it is commonly utilized as seeds and oils in food preparation. The most often used technique for obtaining mustard oil is cold pressing. The output of mustard seeds is 1247 L/ha/year and they contain 30% oil. Because mustard oil has relatively little saturated fatty acids, it is highly unstable.

Coconut trees may grow up to 30 meters tall on average and do well in tropical climates. After being planted for six to ten years, the coconut palm yields 75 fruits per year. Three are two methods for processing coconut oil : wet and dry. While the wet methods uses coconut milk to extract oil, the dry method presses and dries the coconut kernels. About 63-65 percent of a coconut kernel is oil, and 2689 L/ha/year may be produced from it. Myristic acid (48.83%) and Lauric acid (48.83%) are found in coconuts.

Across the world, corn is a staple grain that may also be used to make oil. Corn is grown in vast quantities all over the world. For example, in 2018, 371 million tonnes of corn were produced in the United states. China, Brazil, Argentina, India, and Indonesia followed with 259.2 million tonnes, 97.7 million tonnes, 49.5 million tonnes, 28.7 million tonnes, and 28 million tonnes, respectively. 20% of corn seeds are made of oil, which is typically extracted by pressing them through an expeller and then, for higher output, using a solvent technique. It has a high content of linoleic acid (54.5%) and oleic acid (29.2%).

It is mainly grown in the Asia Pacific region (Friday and Okano 2006). The oil yield from beauty leaf trees is 2000-4000 kg of oil per hectare per year [37]. It has a high concentration of linoleic acid (27.6%) and oleic acid (38.2%). Beauty leaf oil is a great feedstock for biodiesel since it contains 33.4% saturated fatty acids.

2.1.3 Biodiesel feedstocks selection criteria

Lin et al. [38] called attention to the three main thrusts and difficulties to create alternative fuel industry, for example, (i) as sustainable power, biofuel can add to the decrease of GHG outflows essentially when supplanting fossil oil; (ii) it will assume a significant job in reinforcing the country's energy security as the world is facing an energy scarcity situation [iii] the expanded interest of agriculture product for biodiesel production.

It is accounted for that chances, obstacles and even dangers have been raised [39]. The significant parts of biofuel which uncovered the possibility as the cutting edge green fuel, e.g. [i] ecological effect and cost of transformation measure; [ii] difficulties and key drivers of biofuel industry improvement; [iii] endeavors en route for earth benevolent and cleaner discharges; [iv] broadening of items of glycerol from biodiesel; and [v] strategy and motivations from the government.

Anwar [33] defined the various multiple criteria decision analysis (MCDA) processes for finding best possible biodiesel feedstocks. These selection processes were based upon various aspects such as environmental (sustainable use of land and materials), economic (cost of production), technical (physicochemical properties and structural composition), social (end use to customers).

Erdogan et al. [40] evaluated the experimental study on alternative fuel through multi-criteria decision-making models. Nine types of fuel were selected for conducting experimental trial, which are pure diesel, VOB, AFB, and their blends as VOB5, VOB20, VOB50, AFB5, AFB20, and AFB50. The proposed models were good approach to analyse and select the best fuel for improving energy usage in engine. 20% blend of biodiesel with diesel was the best fuel according to the determined criteria in hybrid methods.

Anwar et al. [41] considered the technical aspects of biodiesel for application in the results from the four MCDM for the selection of the best biodiesel feedstocks. Technical aspects include the physicochemical properties, namely density, kinematic viscosity, cetane number, higher heating value, iodine value, oxidation stability, acid value, long chain saturated factor, monounsaturated fatty acid, polyunsaturated fatty acid, cold filter plug point, Flash point.

Anwar [42] focused on various feedstock selection strategies. The five weightage methods include Equal, Critic, Entropy, AHP and FAHP, while five multiple criteria decision-making processes include Promethee, WSM, WPM, TOPSIS, and VIKOR. Another method are based upon 4P (potential, prevalent, popular, and proven) and also includes four different aspects, e.g., technical, economic, environmental, and social considerations. It had been suggested to use advanced feedstock selection performed on FAHP integrated with GRATOPSIS and Fuzzy VIKOR for future research.

Mehra et al. [43] presented an analysis to choose best biodiesel diesel mix for CI engine by applying AHP-TOPSIS based MCDM model. The exhaust emissions from different biodiesel-diesel fuel blends was analyzed. B10 and B20 blends were found to be the best available options for average engine load which can save cost and environment according to comparison of AHP-TOPSIS analysis results.

2.2 Physicochemical Properties of Biodiesel

Researchers have found that the chemical characteristics of the same feedstocks can vary depending on a variety of growing factors, including species differences, temperature, soil conditions, and extraction techniques. The Kinematic viscosity (KV) is a primary fuel property that influences air and fuel mixture, fuel atomization consistency, droplet size, jet penetration, fuel quality, and spray properties [44]. Because lower kinematic viscosity values result in faster engine wear and leaks, a good KV can have a significant impact on engine efficiency. On the other side, bigger droplets during injection from a higher KV gasoline might reduce overall combustion efficiency and raise exhaust gas emissions. Any fuel's energy content is determined by its fuel density. High heating value (HHV) is a measure of a fuel's energy content. A diesel engine needs a high HHV to achieve a better combustion. Since the ideal oxidation stability duration is three to six hours, the addition of antioxidants is required to achieve the proper oxidation stability [45]. The ASTM standards were precisely reached by the oxidation stability of the Jatropha, Coconut, and Beauty leaf, which were 3.02 hours, and 9.2 hours, and 3.58 hours, respectively. One important feature of any fuel is its flashpoint (FP) temperature; a typical fuel should have a high FP. Findings indicate that FP and fuel volatility are inversely related. Biodiesel is far safer to store and transport than gasoline since it has a lower flash point. All of the investigated biodiesels other than Pongamia and Soyabean, meet the minimal specificatons while adhering to all standards.

2.2.1 Biodiesel quality

Biodiesel offers a wide range of fuel qualities because of the presence of both saturated and unsaturated esters [46]. Compared to saturated methyl esters, unsaturated methyl esters have lower freezing and oxidation points. With or without mixing, biodiesel that satisfies the standard quality requirements specified by ASTM-6751, IS 15607, and EN- 14214 can be utilized in diesel engines. Even though biodiesels have poor oxidation stability, they can still be used in diesel engines by adding cold flow improvers and antioxidants. The OSI limitations are 8, 3, and 6 in accordance with American, European, and Indian standards, respectively. Engines using oils or biodiesels as fuels have trouble starting and operating in cold weather. The CFP of oils and biodiesel is determined by the length of the fatty acid chains and the degree of unsaturation [47]. Any biodiesel with a lower CFPP causes issues when used in cold climates, but in warm climates, it can function just fine. CFPP is the lowest temperature at which a specific volume of liquid fuel may still pass through a standardized filtration system in a predetermined amount of time when cooled under specific conditions [48]. Fuel must have a lower CFPP in colder temperatures because fuel thickening can jam, clog, or impede the engine fuel system. For CFPP, there are no worldwide standards. One crucial fuel property that determines fuel's ignition and combustion efficiency is its cetane number. The specific gravity and heating value of the fuel have a significant effect on CN. A higher CN fuel contributes to easier combustion and a faster cold start for engines. It also lessens the production of white smoke. Reduced cetane number fuel produces more particulate matter and unburned hydrocarbons, which also raises engine noise. With the exception of soybean, the majority of biodiesel has CN that is comparable to diesel.

Oxidation stability, which is a key factor in fuel stability and, by extension, engine efficiency, is the capacity of a biofuel to maintain its qualities over extended periods of time. The hydroperoxide, sediments, and gums that are produced when unsaturated fatty acids and/or esters react with ambient oxygen are detrimental to the performance of biofuel engines. The Oxidation Stability Index, or OSI, can be used to determine the oxidation stability of biofuels. Biodiesels which are having poor oxidation stability can also be used in diesel engines after adding Antioxidants and cold flow improvers [49].

The degree of unsaturation, as well as the length of fatty acid chains, determine the CFP of oils/biodiesel. In cold weather, a lower CFPP of any biodiesel creates problems in engine use, but the same biodiesel can work fine in the tropical environment [50]. The lowest temperature at which, when cooled under certain conditions, a certain volume of liquid fuel still moves through a standardized filtration system in a given amount of time is referred to as CFPP . For fuel to be used in cold weather, CFPP has to be lower as the thickening of fuel can jam, clog, or obstruct the engine fuel system [51].

Fuel’s specific gravity and heating value have a major impact on CN [52]. Oxidation stability refers to a biofuel's ability for being stable in its properties when kept for longer duration, and it's a major concern in terms of fuel stability and, consequently, engine efficiency [53]. The reaction of unsaturated fatty acids/esters with atmospheric oxygen produces hydroperoxide, sediments, and gums, all of which harm biofuel engine results. The oxidation stability of biofuels can be calculated using the OSI (Oxidation Stability Index) as shown below [54].

2.2.2 Biodiesel as a Fuel for CI Engines Combustion

A heat engine converts fuel’s chemical energy into thermal energy and uses this energy to generate mechanical work [55]. IC engines find its applicability in the sphere of land, sea, and air transportation. IC engines are also used in industries and prime movers for electrical power generation. Maximizing energy efficiency is a core aspect of sustainability [56]. It involves using energy more efficiently to reduce waste and minimize energy consumption for a given level of service.

Extensive research work on utilization of biodiesel from variety of feedstocks in CI engines have been carried out by researchers throughout the world. Through their published work it is conveyed that despite of different chemical structure of biodiesel, diesel engine can be made to run on it. Biodiesel is blended with conventional diesel to fuel diesel engines in most of the experimental work. At lower blending ratio, e.g., 10% of biodiesel and 90% of conventional diesel, engine offers almost equal thermal efficiency close to diesel fueled engines. Combustion, performance and emission characteristics are obtained by experimental trials of a diesel engine, run on blends of biodiesel from various feedstocks and mineral diesel.

Table 3.1 Physico-chemical properties and reference test methods of biodiesel as per ASTM standards

Property	**Reference Test Methods***	**Grade No.1-B S15**	
		(B100)	**(B6 to B20)**
Sulfur, ppm, max	D5453	15	15
Monoglycerides, % mass, max	D6584	0.40	-
Calcium and Magnesium, combined, ppm, max	EN14538	5	-
Flash point (closed cup), °C, min	D93	93-130	52
(1) Methanol content, mass%, max	EN14110	0.2	-
Water and sediment, % volume, max	D2709	0.050	0.050
Kinematic viscosity, mm^2/s, 40°C	D445	1.9-6.0	1.9-4.1
Sulfated ash, % mass, max	D874	0.020	0.010
Copper strip corrosion, 3 h @ 50°C, max	D130	No. 3	No. 3
Cetane number, min	D613	45	(40)
Carbon residue, % mass, max	D4530 (D524)	0.050	(0.35)

Acid number, mg KOH/g, max	D664	0.50	0.30
Total glycerin, % mass, max	D6584	0.240	-
Distillation temperature, 90% recovered, °C, max	D1160	360	343
Sodium and potassium, combined, ppm, max	EN14538	5	-
Oxidation stability, hours, min	EN15751	3	6
Biodiesel Content, % (V/V)	D7371	-	6-20
Lubricity, HFRR @ 60°C, (micron µm), max	D6079	-	520

Recent research has shown that biodiesel has the potential to be a power source for sustainable energy in the future. It has been found that engines powered by biodiesel emit fewer greenhouse gases (GHGs) than engines powered by conventional fossil fuels. According to IS 15607:2016 norms set by the Bureau of Indian Standards, biodiesel is made up of mono-alkyl esters of long chain fatty acids obtained from vegetable oils or animal fats. Mono alkyl esters, both saturated and unsaturated, are commonly found in biodiesel. Diesel, on the other hand, is a complicated blend of thousands of hydrocarbons, the majority of which are saturated. The features of biodiesel and diesel, which control the spray, atomization, and vaporization processes and hence impact combustion and emissions formation, are greatly influenced by the differences in their molecular structures and compositions [57]. Diesel has a lower density than biodiesel; the difference in density is dependent on the purity and composition of the biodiesel. As can be seen, the allowed ranges for diesel and biodiesel densities are 0.82-0.86 g/cm3 and 0.86-0.9 g/cm3, receptively. In engines with a mechanical fuel injection system, the density of biodiesel affects the start of dynamic injection timings, which in turn affects the ignition delay time. Density is higher in neat saturated methyl esters with shorter chain lengths and lower molecular weights [58]. Viscosity is a measurement of the fuel's resistance to free flow at a specific temperature. Fuel with an excessively low viscosity can cause the fuel injection system's components to not be properly lubricated. A gasoline with a high viscosity increases the power needed to pump. Fuel injection pressure and temperature, for example, have an impact on fuel viscosity, which determines the properties of fuel spray break-up. Reynold's number decreased because of the fuel's increased kinematic viscosity, stabilizing the injection nozzle flow. Diesel is less viscous than biodiesel. According to ASTM standards as given in table 3.1, the limits for biodiesel's kinematic viscosity at 40 ^{o}C are set at 3.5 and 5 mm2/s and 1.9-6 mm2/s, respectively [57]. Temperature has a significant impact on biodiesel viscosity in addition to composition. It seems that at higher temperatures, the viscosity of biodiesel decreases, leading to better spray and atomization properties. The amount of heat required to transition a unit quantity of fuel from the liquid to the vapor phase without causing a change in temperature is known as the latent heat or enthalpy of vaporization. According to reports, biodiesel may stay in the liquid phase for a longer period of time than diesel since it has a higher latent heat of fuel vaporization [59]. Since the effects of latent heat of fuel vaporization on spray characteristics are well-established, this thermophysical parameter is valued highly in studies pertaining to spray and combustion modelling [60]. One important factor influencing the breakage of fuel droplets and the subsequent atomization of fuel spray is the fuel's surface tension [61]. A decrease in fuel surface tension is observed to result in a smaller fuel droplet diameter; conversely, an increase in fuel surface tension increases the difficulty to break up the fuel film at the spray's outer periphery, which impairs fuel-air mixing and atomization. Saxena et al. found that when biodiesel was compared to diesel, it had a longer penetration length and a shorter spray cone angle [62]. Kumar and Gautam reported similar results, attributing them to biodiesel's greater boiling point and latent heat of vaporization compared to diesel [63]. There are reports that biodiesel causes weaker atomization due to its narrow cone angle, longer spray penetration length, and higher density, surface tension, and viscosity compared to diesel. It also reportedly has a lower vapor pressure [64].

Use of biodiesel in CI engines are motivated because it results in considerable decrease of HC, CO and particulate matters emissions. Though there is slight increase in NOx emissions with the use of biodiesel in diesel engines, no sulphur and aromatics are found in exhaust gases. The best part of biodiesel use lies in its ability to be utilize without design modification in diesel engine.

2.2.3 Merits of Biodiesel

The following merits of biodiesel attracts the research community to explore it as an alternative to diesel fuel [65].

- Most of the biodiesel has a higher cetane number, which makes it a better fuel as higher is the cetane number, better is the combustion.
- Oxygen content in biodiesel is more as compared to diesel, which improves the combustion quality.
- Biodiesel is cheaper than diesel as latter is obtained by complex distillation processes.

- Biodiesel production is easier and is less time consuming than conventional diesel.
- Biodiesel can be obtained by various sources that can be grown as a crop, which make it a renewable fuel.
- Combustion of biodiesel is less polluting than petroleum diesel and so it can be considered as a environment friendly fuel.
- It is biodegradable and non-toxic.
- It can be used in conventional diesel engine without engine modifications.
- Use of biodiesel ensures better fuel economy and a positive economic impact on country as it can reduce dependence on imported fuel.
- Biodiesel is safe to handle, store and transport; because of its much higher flash point than diesel.

2.2.4 Limitations of biodiesel

The following limitations of biodiesel are important to be considered for improving its combustion characteristics.

- Due to various feedstocks, quality of biodiesel varies depending on its source.
- Biodiesel has a low volatility than biodiesel which makes it difficult during ignition.
- It has high viscosity due to which there is fluidity problem.
- Combustion of biodiesel produces more Nitrogen Oxides than diesel.

2.3 Review on Combustion, Performance, and Emission Characteristics

An exhaustive literature review has been carried on combustion, performance, and emission, which are summarized below:

Verma et al. [66] did a comprehensive review on combustion characteristics, engine performance and emissions of biodiesel fuel in CI engines. The power produced from engine depends upon the calorific value of the fuel. Thermal efficiency can be improved by improving the combustion quality. Higher cetane value of fuel leads to lower ignition delay and so improves the air-/fuel rate and combustion process. Particulate matters include carbon, sulphur, nitrogen etc. as its emission. Use of B20 in CI engines reduce PM emissions by 22% compared to regular diesel fuel.

Kumar et al. [67] reported the influence of fuel injection pressure and fuel injection timing on the combustion, performance, and emission characteristics of jatropha biodiesel as pilot fuel used in hydrogen dual fuel engine. The maximum HRR was found at 1500 bar injection pressure and with increase in injection pressure brake thermal efficiency improves marginally. Also increase in injection pressure, increases the NOx emissions because it improves the combustibility of charge.

Nema et al. [68] concluded that air-fuel mixing improved at higher compression ratio. The sucked-in air temperature was on the higher side at higher CR, which helps in better atomization of fuel and improved fuel combustion inside the combustion temperature. Also, the higher CR favours the high rate of NOx formation and higher exhaust gas temperature.

Kanimozhi et al. [69] reported that with increase in engine load there was slight drop in brake thermal efficiency. For higher biodiesel blends concentration, no changes observed in HC emissions at different engine loads. At lower engine loads, NOx emissions were found to be lower. From 25% to full load condition, the incremental change in NOX emissions were 500 ppm.

Razzaq et al. [70] reported that with an increase in engine speed; BTE increases, BSFC decreases, Brake power increases, and increase in EGT. At higher engine speeds, CO emissions were reduced, HC emissions were reduced, and an increase in NOx emissions.

Perumalla Vijaya Kumar et al. [71] presented the evaluation of POME blends of 10-20-30% for obtaining combustion attributes at different compression ratios and using EGR techniques. Compression ratios of 16, 18, and 20 were taken for investigation. The minimum cylinder pressure was obtained at CR of 18, while BTE was maximum at CR of 20. 20% blend of biodiesel with 6% EGR condition at a compression ratio of 20 was found to be the optimum condition for obtaining best results.

Nabi et al., [72] emphasized that due to economic issues, energy scarcity, and environmental degradation, it is necessary to focus studies on biofuels. Their research aims to investigate the performance, combustion, and emissions using waste tire oil-Diesel-Glycine max biodiesel blends. Exergy, and energy values were obtained at different engine speed. The combustion parameters like cylinder pressure, rate of heat release, gross heat release, exhaust temperature etc., were obtained at different crank angle. The performance parameters like brake thermal efficiency, brake torque, brake power, brake specific fuel consumption, brake mean effective pressure etc., were found for different engine speed. In addition to these results, engine noise measurements for all blends of biodiesel and diesel fuel at a wide operating engine speed were also conducted.

2.4 Review on Energy and Exergy

An exhaustive literature review has been carried on thermodynamic performance of biodiesel fueled engine of which some of the important literature outcomes are summarized below:

Sekmen and Zeki [73] did energy-exergy analysis through experimental work on diesel and soybean oil and its blends. They found that biodiesel yields 1.3% higher thermal efficiency than diesel. For diesel and biodiesel, the fuel exergy input lost are 6.49% and 7.31% as heat transfer. The exergetic efficiencies are 6.8% and 6.2% lower than the corresponding brake thermal efficiency.

Özkan et al. [74] performed experiments with predefined injection strategies for energy-exergy analysis on diesel (graded according to EN590) and found that pre-injection strategies reduce the brake work and increase the exergy. The exhaust loss is 25.35%, the exhaust exergy is 7.94%, the cooling loss is 14.31%, and the cooling exergy is 1.92%.

Jena and Misra [75] found the effect of oxygen on energetic and exergetic efficiency of Palm and Karanja oil by performing experiments and by applying thermodynamic equations for exergy calculations. The uncounted exergy destroyed (mainly due to combustion irreversibility) was the minimum, whereas brake thermal efficiency and exergetic efficiency is maximum. Further, palm biodiesel is found to be better than Karanja biodiesel in terms of both energetic and exergetic performance.

Panigrahi et al. [76] did the energy-exergy balance calculations on Mahua oil through heat balance sheet and found that the fuel energy input of diesel is 6.25%

more than B20 due to high heating value of diesel. The exergy efficiency of diesel and B20 was 30.66% and 28.96%, respectively. The input availability of diesel fuel is 1.46% more than B20. Shaft availability of diesel is more than that of B20. Exhaust gas availability of diesel is more than that of B20. The system inefficiency is the destructed availability which is found more in case of B20.

Aghbashlo et al. [77] improved the energetic and sustainability parameters of a DI diesel engine fuelled by waste oil extracted from spend bleaching earth (SBE) by performing engine tests and measuring input and output values. Exergy rate was 6.5% higher than corresponding energy rate, the exergy flow rate of the exhaust gas increased with increasing engine load, The exergy transfer rate to the ambient air increased drastically with elevating the engine speed and load.

Karimi [78] performed the exergy-based optimization of direct conversion of microalgae biomass to biodiesel using RSM and ANN to find the optimum yield. The most exergy efficiency was found to be 81.45% with enhanced yield by increasing ultrasonic power and reaction time.

Madheshia and Vedrtnam [79] did the energy-exergy analysis of waste cooking oil and mustard oil by preparing heat balance sheet for an engine at varying load and speed. The B.P. is influenced most by the load, followed by the type of oil and speed has the least effect.

Marziyeh et al. [80] performed **e**nergy and exergy analyses of diesel, biodiesel-diesel blend by representing engine as a control volume. Waste cooking oil was blended with diesel to perform experimental work. Gasoline fumigation increases the energy and exergy efficiency at medium and high loads to about 5% for diesel baseline fuel, while the energy and exergy efficiency decreases slightly in case of B20 fuel with gasoline fumigation. For all operating points, the percentage of energy and exergy transfer through the exhaust gases decreases by an average of 2.6% and 6.4%, respectively in case of using gasoline fumigation for both diesel and B20 fuels.

Murugapoopathi and Vasudevan [81] obtained BTE, FFR, BP, BSEC, and EGT for compression ratios from 18:1 to 22:1 for different blends by performing energy exergy analysis by taking methyl esters of rubber seed oil. The destructed availability decreases for lower blends of biodiesel at 4.55% by increasing CR. Shaft availability of lower blend increases by 14.95% at CR 20. However, cooling water availability in fuel input and biodiesel blends observed are very low.

Yesilyurt and Arslan [82] obtained the effects of the fuel injection pressure on energy and exergy efficiencies by changes in engine load, engine torque and fuel consumption on the blend of waste cooking oil and canola oil. The energy and exergy efficiencies of the engine fuelled with biodiesel were improved when increased from 170 to 210 bar. Exhaust exergy rate, cooling water exergy rate, and heat transfer exergy rate are the factors that decrease the exergy efficiency.

Chaudhary and Gakkhar [83] evaluated the exergetic and energetic parameters by experimental work on blend of WCO and Neem oil fuelled DI diesel engine. At 100% load, the exergetic efficiency for NEEM15 and WCO15 is 28.95 and 30.48%, respectively. NEEM15 gives higher exergy destruction as compared to WCO15.

Sanli and Uludamar [84] analyses **e**nergy and exergy of a Diesel, hazelnut biodiesel, and canola Biodiesel fuelled diesel engine at various engine speeds. The lowest destruction occurred at 1800 rpm for all test fuels with the value of 45.45%, 47.36%, and 47.41% for diesel, hazelnut biodiesel, and canola biodiesel, respectively.

Karagoz et al. [85] determined the exergy-based sustainability indicators for waste cooking oil and diesel blends when fuelled in CI engine. The exergy efficiencies of the test engine for D90B10 and D90B10Al2O3 were determined to be 25.57% and 28.12%, respectively.

Sanli et al. [86] assessed the thermodynamic performance of an IC engine by analysing the exergy and energy and the effect of the ambient temperature on diesel fuel and microalgae biodiesel. The energetic and exergetic efficiencies for the engine using diesel fuel were slightly higher than those of the engine using MAB fuel. With increasing the ambient temperature, the destruction exergy rate increased while both heat transfer exergy rate and exhaust exergy rate decreased.

Nabi et al. [87] did the assessment of energy and exergy parameters using ethanol-diesel blends by developing the thermodynamic model to simulate and analyse the different parameters. The energetic and exergetic efficiencies were higher at a lower oxygen ratio for all fuel blends.

Duarte-Forero et al. [88] found the influence of hydroxy gas enrichment in a biodiesel blend by assessing the energy, exergy, and emissions for commercial diesel and industrial palm oil residues. Hydroxy gas volumetric flow enrichment of 0.225 LPM boosted both energy and exergy efficiencies up to 15.36% and 12.15%, respectively.

Karami et al. [89] analyses the exergy, energy, and emissions on binary and ternary blends of seed waste biodiesel of tomato papaya and diesel by theoretical and experimental investigation. Energy percentage of exhaust emissions were at 30% while this fraction was about 13%. Maximum exergy efficiency was found at about 29.63%.

Djermouni and Ouadha [90] applied the first and second laws of thermodynamics under various values of ambient temperature to perform the thermodynamic analysis of alternative fuels like ammonia, methanol, and hydrogen. The thermodynamic model examined suitability of engine working over a range of engine inlet temperatures. The fuel's physicochemical properties affect the thermal performance and exergetic efficiency.

2.5 Research gap

After the exhaustive review of the literature, the following research gaps were identified:

- Wide variety of biofuels are available throughout the world, investigation of prominent and deserving biofuel is required.
- By-products of various industries are good sources of alternative fuel; finding the feasibility of usage by exploring its performance and combustion analysis is needed.
- The effect of operating parameters on thermodynamic behaviour of biofuel is yet to be discovered, to be used at mass level.
- Limited work has been explored on the effect of engine geometries on combustion and performance of biodiesel fuelled CI engine.

- The effect of altering fuel properties by physical methods (e.g. preheating) needs more investigation.
- The effect of biofuel behaviour for various engine types (based on no. of cylinders, etc.) are yet to be explored.
- Little effort had been made on selection of biofuel feedstock on case to case basis in most of the research work done so far.
- A Very little emphasis is being given on thermodynamic analysis of biodiesel fuelled engine.
- Several setup for engine working on pure diesel was modeled in literature are available, but similar kind of setup for biodiesel fueled engine are still lacking.
- Very little work is available on the effect of operating parameters on thermodynamic availability of biodiesel.
- Most of the work in the field of alternative fuel were experimental in nature; Simulation tools are scarce in available literatures.

2.6 Problem Statement

The study of current energy scenario suggested the need for extensive research in the field of alternative fuel. The thorough literature review identified the potential sources of biodiesel and the need for their performance and combustion analysis. The study of physical and chemical properties of fuel were important for showing resemblance to the conventional fuel. It has been noted that performance and combustion study of biodiesel fueled conventional CI engine are necessary for primary study of any fuel and to understand its combustion characteristics. An energetic and exergetic study of any particular fuel will be the ultimate step to establish it as a sustainable fuel. The technological feasibility of blended biodiesel could be established by following these studies. The current study includes all the necessary steps for investigating the viability and impact of blended tallow biodiesel use in conventional diesel engines.

2.7 Research objectives

1. To select tallow oil as an alternative fuel and produce biodiesel from it.
2. To develop the engine setup for experimental study of the effect of operating variables on the performance and combustion of tallow oil fuelled CI engine.
3. To study the effect of altering fuel properties by physical methods on the performance of the CI engine.
4. To study the effect of engine parameters on the thermodynamic behavior of Tallow biodiesel fueled engine.

CHAPTER 3

FUEL FOR COMBUSTION

3.1 Selection of Fuel

The previous chapter emphasized various selection criteria to choose better alternative out of the available biofuel resources. The available feedstocks for biofuel production have been studied through exhaustive literature survey. Free fatty acid in biofuel mainly decides the quality of biofuel and fatty acid composition was noted for few widely available feedstocks. Physicochemical properties of generally available feedstocks are also summarized. This work extensively contributed in identifying the most appropriate and cost-effective feedstocks for biodiesel selection for greater use. Waste cooking oil, because of its easy and wide availability and Tallow oil, because of its economic viability and being environmentally friendly fuel; are two important biodiesel feedstocks were considered suitable for use as an alternative to fossil fuels for experimental work. Though, numerous works were found on WCO; literature on Tallow biodiesel was limited. The experimental work carried out on Tallow biodiesel was limited to performance and emission analysis. So, the present work was aimed at carrying out more exhaustive analysis, which includes performance, combustion, emission as well as thermodynamic analysis.

3.2 Effect of altering fuel properties by physical methods

Rudolf Diesel in his demonstration of patented diesel engine used peanut oil as a fuel. Since then, quest for alternative fuel started among research community. After carrying ample research works, direct use of neat vegetable oil is prohibited for diesel engines; because of their different physico-chemical characteristics [91]. The problems so far encountered while using vegetable oils directly are discussed below:

(i) Abnormal combustion may occur, which can cause engine wear also.

(ii) The heating value of vegetable oils are lower than diesel due to presence of chemically bounded oxygen.

(iii) The vegetable oils are found to be less volatile than diesel due to higher viscosity and high flash point.

(iv) The higher cloud and pour points of vegetable oil causes cold starting problems.

(v) Direct use of vegetable oils also cause plugging and gumming of injector and delivery lines.

(vi) Carbon deposits on various engine parts such as piston, piston rings, valves, engine head, injector tips.

(vii) Engine knocking problem are faced by direct use of vegetable oils.

3.2.1 Blending

The major goal of altering fuel properties is viscosity reduction to prevent flow and combustion-related issues. One method for bringing the viscosity near to a certain range is to blend vegetable oil with diesel or another fuel. Experimental trail on CI engines have been carried out after mixing of various vegetable oils with mineral diesel. These studies shown that it was impractical to replace 100% of diesel fuel with vegetable oil, although a 20% blend of vegetable oil and diesel performs satisfactorily in the current diesel engine and operating conditions. Numerous studies claim that mixtures of vegetable oil and diesel have higher brake specific fuel consumption (BSFC) and exhaust gas temperatures than pure diesel. Vegetable oils can be blended to minimize viscosity, however because the molecular structure is unaltered, polyunsaturated character and low volatility issues still persist. Also, it was found that BSFC increased as the blend's vegetable oil content rose. It was concluded in most of these studies that at lower blend proportions, the CI engine's performance and emission characteristics were only significantly different from base diesel. Due to the low calorific value, high density, and high viscosity of biodiesel in comparison to diesel, there is an increase in the consumption of biodiesel, which results in a decrease in engine power and thermal efficiency [92]. The high viscosity of biodiesel also interferes with the injection process, which resulted in poor fuel atomization, incomplete fuel combustion, significant smoke opacity, and high carbon buildup on the injector and valve seat [93]. These issues can be checked by blending of biofuels with diesel, which transforms biodiesel at par with diesel. By improving the characteristics of conventional gasoline and combining it with alternative fuels and nano-particles, engine characteristics have also been optimized [94]. Biodiesel has a higher oxygen content than other fuels and nearly equals diesel fuel in terms of cetane number and calorific value. As a result, biodiesel with a higher oxygen content ensures better combustion and produces fewer CO and HC emissions [95]. Alcohols, with the exception of biodiesel, have lower calorific values than traditional fuels, which promote higher specific fuel use [96]. They also have less cetane numbers, which ensure better control over the combustion phase. In addition to alcohols, Compressed Natural Gas (CNG) can ensure better combustion and a more homogenous mixture, both of which lead to reduced emissions of hydrocarbons. Furthermore, a higher oxygen concentration in CNG gas encourages quick burning, which raises the temperature inside the cylinder and raises emissions of nitrogen oxide.

3.2.2 Preheating

One of the most efficient strategies for reducing the viscosity of oils is preheating. It must be raised to a temperature high enough to produce a low viscosity equivalent to diesel, but not so high that it damages the injection system. Previous studies show that preheating biodiesel at temperatures ranging from 25 to 100 ^{o}C lowers their viscosity to that of diesel, and that at temperatures above 70 ^{o}C, biofuels have viscosities similar to mineral diesel. Numerous experiments were performed to obtain data for efficiency and emissions of diesel engines that ran on heated biofuels like Pallm, rapeseed, and Jatropha, among others. According to their findings, using preheated biofuels in diesel engines increased brake thermal efficiency (BTE). In most circumstances, a diesel engine running on preheated biofuels emit more nitric oxide (NO) and hydrocarbons (HC) than a diesel engine running on regular gasoline.

3.2.3 Microemulsions

To lessen the viscosity of vegetable oil, micro-emulsions with solvents like methanol, ethanol, and iso-butanol have been explored. A micro-emulsion is described as a spontaneously generated colloidal equilibrium dispersion of optically isotropic fluid microstructures with size typically in the range of 1-150 nm. Through the explosive vaporization of the low boiling elements, they can enhance the spray properties. Numerous studies on the characterization of microemulsions of animal fats and other biofuels have been carried out. Furthermore, the studies on emulsion of biofuels suggest that due to advancement in the atomization process, it is suitable as diesel engine fuel. However, this may cause rise in BSFC, ignition delay, HC, and carbon monoxide (CO) emissions.

3.2.4 Pyrolysis

Pyrolysis is the process of using heat in the absence of air to convert complex hydrocarbon structures into simpler ones [97]. Animal fat and vegetable oils can both be pyrolyzed to be used in the diesel engines in the past. The pyrolysis of fats for fuel were common in regions where petroleum reserves are scanty. This process is conducted at faster heating rates and temperatures in the range of 250-500 ºC. Pyrolysis process has the potential to provide a variety of useful compounds as well as fuel for gas turbines, motors, and combustion chambers. The feedstocks, uses for the products, appropriate reactors, and methods for the product applications all influence the complexity and chemical instability of the bio-oil mixes. There are a few problems which prevent its easy utilization and further industrialization, such as stabilizing before using it in heating application and electricity generation.

3.2.5 Transesterification Process

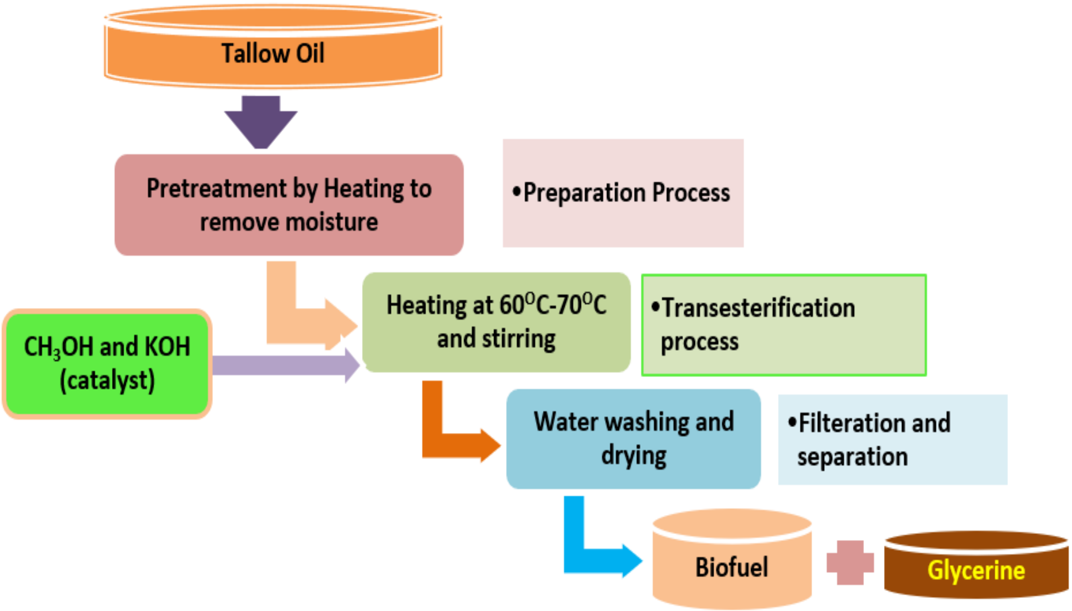
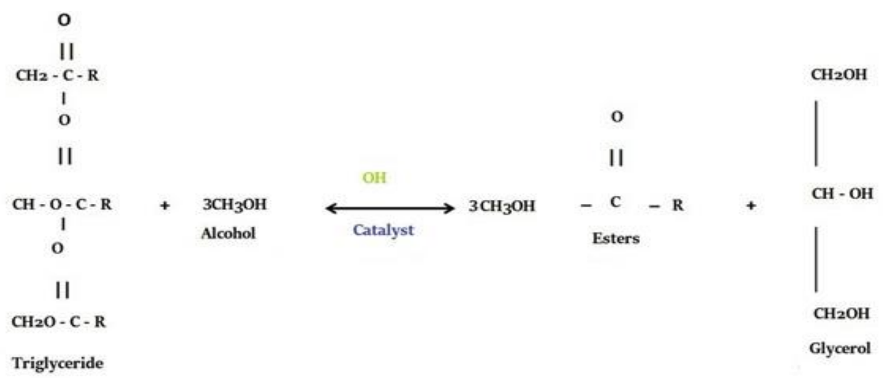


Fig. 3.1 Schematic diagram for the production of biodiesel

The transesterification process converts the triglycerides of any oil into straightforward mono-esters as per equation 1 [98]. Triglycerides and alcohol are combined during the transesterification process to create glycerol and fatty acid esters. Typically, a catalyst is utilized to speed up the reaction and increase the yield. This procedure lessens its unsaturation and viscosity. The most significant factors affecting the transesterification reaction are the temperature of the oil, the alcohol to oil ratio, the type and concentration of the catalyst, and the pace of stirring, the degree of mixing, and the purity of the reactants. In the transesterification process, reaction takes place in the presence of a catalyst (KOH) to produce different esters e.g., methyl esters from methanol, ethyl esters from ethanol, butyl esters from butanol etc. 40% methanol and 15 NaOH are determined to be the ideal inputs for this process [99]. After 90 minutes of reaction time at 60 ^{o}C, the maximal yield of ester is obtained. Theses esters are normally referred as biodiesel. The biodiesel has characteristics that are more similar to those of mineral biodiesel. The most significant benefit is that the Kinematic viscosity is decreased to almost diesel-like levels. The cetane number and calorific value are also improved. The schematic representation of biodiesel by transesterification process is shown in Fig. 3.1. Both methanol and ethanol are utilized in this procedure, however methanol is frequently used due to its accessibility, affordability, and strong reactivity [100]. However, ethanol has benefits including being environment friendly, renewable, and can be obtained from agricultural produce.



……..(1)

Many countries have drafted their own biodiesel standards. However India follows IS: 15607 as a standard for the manufacturing of biodiesel. Table 3.2, which displays the limiting values of some of the features of Tallow biodiesel in ASTM and IS :15607 standard, contains all the previously mentioned standards. Tallow oil was used as the raw material to produce ester of tallow for the present investigation. Table 3.1 lists the fatty acid components found in Tallow oil. For all of the criteria listed in standards, the limiting value of carbon residue is essentially the same. When biodiesel is injected into a diesel engine, one of the general biodiesel factors that has significant impact on the spray production is viscosity. To prevent adverse effects on the performance of a fuel injector system, it is crucial to keep the viscosity of fatty acid methyl ester within the range of permissible limits [101]. As a result, the suggested viscosity parameters are almost identical to those of diesel fuel.

3.3 Preparation of Tallow Methyl Ester - Diesel Fuel Blends

The goal of the current study is to assess how fuel mixtures of tallow biodiesel and diesel at different blends affect a direct injection (DI) diesel engine’s combustion performance, and emissions characteristics. To create a uniform, stable combination, the mixture was thoroughly churned with the aid of a mechanical stirrer. To confirm its stability, the blends were all monitored for 72 hours and no changes in physical appearance was observed. To prepare the blends for the experiment, tallow biodiesel was mixed with diesel at 10%, 20% and 30% on volume basis [102].

3.4 Determination of Physicochemical Properties of Tallow Biodiesel

This study evaluates the significant physico-chemical characteristics e.g. density, viscosity, calorific value, oxidation stability, distillation point, flash point, cold filter plugging point (CFPP), moisture content, carbon residue, copper strip corrosion of Tallow oil and its methyl ester in accordance with ASTM D 6751 standards. Along with the equipment used for calculation with their make, some of the properties are also covered. The fuel analysis, shown in table 3.2, comprises quantitative measurements of the fuel parameters of biodiesel and diesel for comparison, as well as carbon, hydrogen, nitrogen, sulfur, and oxygen. The features of a liquid fuel, such as its potential performance in a combustion system, storage and transport concerns, possible emissions, distillation range, etc., are determined by its physico-chemical properties. The temperature at which flammable gases are formed and will ignite, or the flash point, of a liquid fuel, shows the fire risks that come with its usage, storage, and transportation. Due to the variations in boiling point it has a low flash point as compared to petroleum refined fuels. The carbon residue test evaluates the oil's propensity to generate carbon under poor combustion environments, which may result in carbon coking of spray combustion or fuel injector nozzles in diesel engines. A Fuel's viscosity affects the process of atomization during combustion process. The tallow biodiesel has properties similar to that of petroleum diesel.

Table 3.2 Properties of Diesel and Tallow biodiesel

Properties	**Standard Method**	**Diesel**	**ASTM D6751-12**
			Tallow Biodiesel
DENSITY @25^{0}C (kg/m3)	ASTM D4052	830	873.2
Specific heat capacity (J/kg K)	ASTM E1269-11	2090	1774
Heating value (KJ/Kg)	ASTM D4868-17	42000	38350
Kinematic Viscosity @30^{0}C (mm^2/s)	ASTM D445	3.2	5.85
Latent heat (J/ kg)	ASTM D4809-18	277000	229327
Vaporization temperature (^{0}C)	ASTM D 86-19	341	341
Boiling point (^{0}C)	ASTM D-1120-17	204	418.2
Volatile component fraction (%)	ASTM D86-19	100	100
Binary diffusivity (m^2/s)	ASTM F1769-97	3790000	7420000
Cetane Number	ASTM D613	49	56
Flash Point (^{0}C)	ASTM D93	53	163
Chemical Formula	IUPAC	$C_{16}H_{28}$	$C_{53}H_{102}O_6$
Carbon content (% mass)	ASTM D4530-15	86.7	77.6
Hydrogen content (% mass)	ASTM D3343-16	12.8	12.7
Oxygen content (% mass)	-	-	11.35

3.4.1 Density

The density of the fuel was determined using the “Antan Par Density Meter”, Model DMA 4500, as indicated in Fig. 3.1. The current inquiry includes the determination of the specific gravity of a test fuel sample at 150 ^{o}C in accordance with ASTM D-4052 criteria. This instrument operates on the basis of U-tube oscillation, in which the density of liquids and gases are measured by the frequency of oscillation [103]. The frequency is measured using a spring-mass system. The sample of 10 ml was introduced into the instrument’s port after cleaning the test fuel pipeline with 10 ml of Toluene. The same pilot fuel was replicated five times, and the final figure was taken as the average of these values.

3.4.2 Kinematic Viscosity

Viscosity measurement and their variation with temperature can provide a better understanding of tallow biodiesel for use as a combustible fuel for CI engine. The viscosity of different biodiesels at varying temperatures was measured using a viscometer. Fuel viscosity was determined at 40 ^{o}C using a “Petrotest Viscometer” in accordance with ASTM D-445 standards [104]. Following the flow of the sample containing the calculated entity via the capillary tube, the timing of the fuel leveling from the lower level to to the upper level mark was measured. Equation 3.4 illustrates how the kinematic viscosity is then calculated by multiplying the time duration by the capillary constant.

$$v=k*t \tag{2}$$

Where, v stand for kinematic viscosity (mm2/s); k stand for (k=0.005565) capillary constant (mm2/sec2), time (in seconds), respectively.

Moreover, fuels with high viscosity properties cause problems for supply lines and fuel injectors [105]. As a result, high viscosity fuel has trouble atomizing the fuel, which makes it harder to combine the fuel evenly and causes unburned hydrocarbons and particulate matter to escape.

3.4.3 Calorific Value

Calorific value is defined as the quantity of heat produced by burning a unit mass of fuel under particular conditions in a calorimeter, where high heating value is the entire amount of heat created in the combustion process of oxygen with carbon and hydrogen, which produces carbon dioxide and steam, and then condenses by releasing heat in KJ/kg. The calorific value was determined as per the ASTM D240.0 standard using an isothermal bulb calorimeter and, where the fuel is burned at a constant volume in an adiabatic water tank in the presence of oxygen. The ignition happens in the fuel sample and combustion occurs in the bomb calorimeter, after which the rise in the temperature in the thermocouple is monitored and the calorific value of the test sample is calculated. The “Parr Model 6100EF” equipment model was used to measure the calorific value of biodiesel and its mixes in the laboratory.

Engine performance parameters are more influenced by the calorific value than by the fuel qualities [106]. Higher calorific value fuels release more energy, which means that less fuel is needed to produce the same amount of power as before. This suggests that higher calorific value fuels can lead to better specific fuel consumption [107]. Furthermore, larger calorific value fuel contributes significantly to thermal efficiency through power output.

3.4.4 Flash Point

The flash point is the lowest temperature at which oil vapors produce an ignitable combination as air interacts with oil droplets, resulting in a flash [108]. This is tested using a Pensky-Martens flash point equipment, and the flash point of the test fuel is estimated using ASTM D93 standards. At constant time intervals, the fuel sample was heated to a small pilot flame in a test cup via the upper lid. The lowest flash point was 1300 ^{o}C, as tested by ASTM D-6751 and EN-14214.

Plate 3.1: Density meter

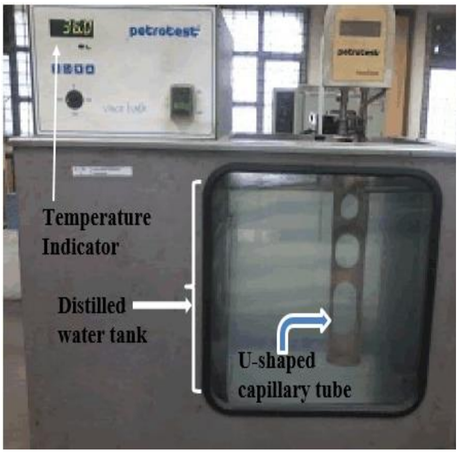


Plate 3.2: Viscometer

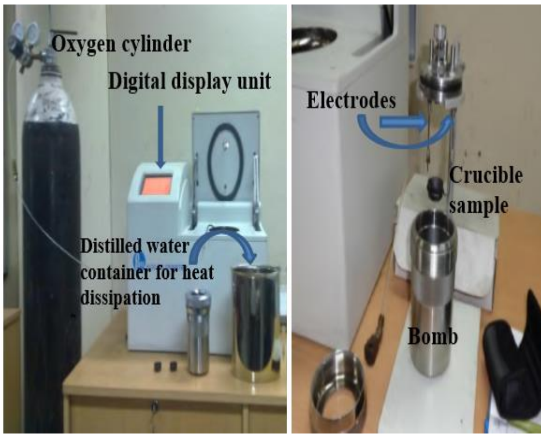


Plate 3.3: Bomb calorimeter

Plate 3.4: Flash point tester

3.4.5 Cetane Number

The cetane number (CN) is a measure of the ignition quality of diesel engine fuel. The quality of ignitibility in CI engines is defined by the property of petroleum diesel or diesel like fuels. The fuel attribute known as cetane number is essential to combustion phasing; fuels with a higher cetane number accelerate combustion and cause issues with phase control. The cetane index is calculated using the ASTM D4737 standard in this study. As a result, the cetane index and density curve of several fuel samples were determined using distillation [109].

3.4.6 Carbon Residue

The quantity of carbon that remains/is deposited in the combustion chamber as a result of the burning of liquid/gaseous fuel. The Micro Carbon Residue Tester (MCRT160) is used to calculate the carbon residual in accordance with ASTM D4530 measurement criteria. Initially, a 5 gm weighted fuel sample is placed into the sealed crucible of the MCRT160. Furthermore, the combustion progressed smoothly to 500

^{o}C at 100 C/min intervals, and the combustion lasted for 15 minutes. Second, and ultimately, remaining combustion products are cooled by removing nitrogen gases from the system. When the temperature of the test tube goes below 300 ^{o}C and traces or residues remain in it, it is weighted.

3.4.7 Distillation

The test sample of 100 ml was distilled according to the ASTM D-86 standards technique in the distillation device. First, the sample is placed in a distillation flask, where the procedure is carried out under certain circumstances. The temperature at which the condensed drop begins to descend from the bottom end of the condenser. Furthermore, at regular intervals of time, the condensate volume is calculated by comparing it to the condensate temperature. Furthermore, the maximum temperature is measured at which all of the fuel is condensed.

3.4.8 Oxygen Content (Wt%)

The availability of oxygen in fuel has a significant influence on CI engine combustion and exhaust species. Higher availability leads to more complete combustion and a reduction in dangerous UHC and CO emissions. Because of variables such as nil sulfur concentration, fuel confined oxygen, unsaturated fatty acids, and lower aromatic content, biodiesel contributes far less soot than normal diesel. As a result, reducing soot production may reduce radiative heat transmission from combustible particles. The oxygen wt% was measured using an EA3000 series CHNS/O elemental analyser in accordance with ASTM D5373 standards. The procedure of detecting oxygen differs slightly from that of measuring hydrogen, carbon, sulfur, and nitrogen. This procedure is comparable to a combustion reactor in that it burns oxygen, 5%

hydrogen using a pyrolysis reactor, which is then dissolved in Helium to identify the oxygen gas. The entire system includes a device for trapping acidic gases, a gas chromatograph column for extracting gas mixtures, and a pyrolysis reactor strengthened with nickelized carbon fiber. Furthermore, the pyrolyzed product was carried out in the setup while helium gas was circulating. First the fuel sample is inserted in the reactor and heated to 1080 ^{o}C, resulting in sample breakdown and oxygen gas emission. The nickel carbon wool then combines with oxygen to produce nitrogen and carbon monoxide. The pyrolyzed product is separated by passing it through a GC separation column, where gases are identified and discriminated using a thermal conductivity detector (TCD), where TCD acts as a medium that separates the gases and leads to elemental peaks. As a result, software decodes particular signals and correlates the peak for each element in the sample.

3.4.9 Copper Strip Corrosion

Because of the presence of various types of sulfur and acids in the gasoline, engine components and engine linings corrode. As a result, various fuel samples are exposed to copper strip corrosion tests in order to analyse the fuel specimen. This parameter was tested by immersing the copper strip in the fuel bath for three hours. The bath's fuel temperature was kept constant at 500 ^{o}C. Furthermore, the copper strip was withdrawn from the fuel bath at a certain time period. The extracted strip was then matched to a standard color code ranging from 1 to 4.

The features that are responsible for difficulties in starting diesel engines at a low temperature include emitting white smoke, filter blocking, and injector chocking are cold flow properties. Cold fuel performance is poor and can be classified as cold point (CP), pour point (PP), and cold filter plugging point (CFPP).

Plate 3.5. Distillation setup

Plate 3.6. Carbon residue tester

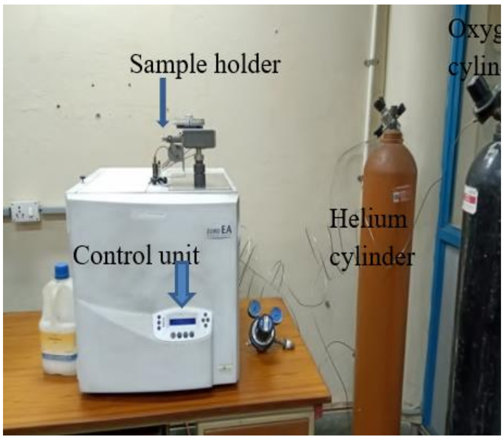


Plate 3.7. CHNS/O Elemental Analyzer

Plate 3.8. Copper strip corrosion tester

3.4.10 Cold Point and Pour Point

the liquid fuel's pour point is the lowest feasible temperature at which the wax in the fuel crystallizes and takes on a hazy look also, it loses its flow properties [110]. The pour point and cloud point were calculated using the ASTM D97 and D2500 standards, respectively [111]. Their measurement as shown in Fig. 3.6 have a test tube with the rubber stopper inside, which is maintained within the hole provided above the refrigerator. The cork has an aperture in the center for an RTD temperature sensor, which measures the temperature of the sample. The test tube is then removed and viewed at every temperature decreases of 300 ^{o}C to simulate pour point measurement and cloud point formation.

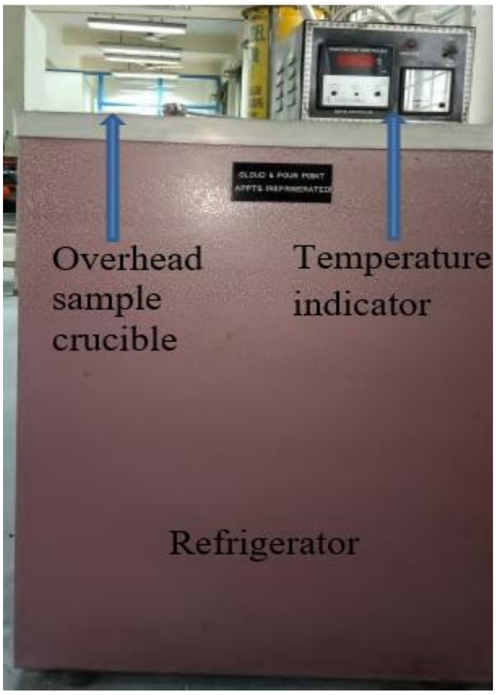


Plate 3.9. Cloud point and Pour point apparatus

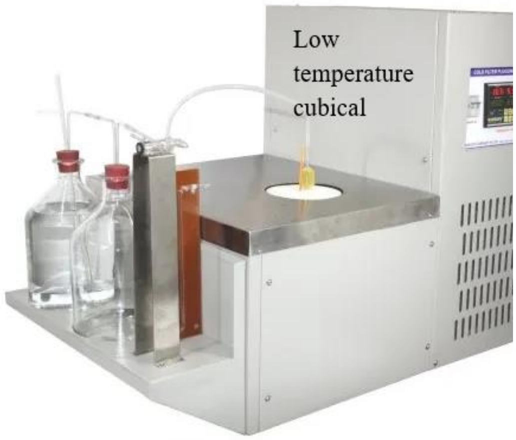


Plate 3.10. Cold filter plugging point apparatus

3.4.11 Cold Filter Plugging Point (CFPP)

The temperature at which test gasoline begins to gel up in such a way that it can flow through a typical fuel filter in a reasonable amount of time is CFPP [112]. It is also defined as the time it takes for the fuel column to become almost stable from ups and downs in a standardized filter of 10 microns. Its values lies between the pour point and the cloud point for gasoline. Linetronic Technologies are used to measure this fuel attribute. It is designed to estimate the cold filter plugging point of biodiesel and diesel blends in accordance with ASTM D6371 standards [113]. The first step is to reduce the bath temperature to -340 ^{o}C. When the temperature reaches the prescribed range, a weighted amount of fuel is pulled into the capillary tube through a vacuum supported mechanism. The temperature of the fuel sample is then allowed to drop in the bath.

3.5 Relevance of Fuel Physico-Properties to Current Study

The physicochemical properties of fuels play a crucial role in the performance and efficiency of combustion processes. This is particularly relevant in the context of biodiesel, where understanding and optimizing these properties are essential for effective utilization. The physicochemical properties of biodiesel are integral to the thermodynamic study of its combustion process. Analyzing these properties allows researchers and engineers to optimize engine design, improve combustion efficiency, and meet environmental standards. Additionally, a thorough understanding of these properties contributes to the development of more sustainable and efficient biodiesel formulations for future energy needs. The importance of individual fuel physico-properties in the thermodynamic study of biodiesel can be highlighted in several aspects:

Viscosity: Viscosity is a critical property that influences the flow behavior of biodiesel. High viscosity can lead to poor atomization and incomplete combustion in engines. The study of viscosity is essential for designing fuel injection systems and ensuring proper mixing with air in the combustion chamber.

Density: Density affects the energy content of the fuel, influencing the combustion efficiency and overall engine performance. Thermodynamic models need accurate density data to calculate parameters such as heat release rates, which are crucial for optimizing engine designs.

Flash Point and Ignition Delay: Flash point and ignition delay are key parameters that influence the ignition characteristics of biodiesel. Understanding these properties is essential for designing engines with optimal ignition timing. Thermodynamic studies can help in predicting ignition characteristics, allowing for the optimization of engine parameters to ensure reliable and efficient combustion.

Calorific Value: The calorific value is a measure of the energy content of biodiesel. Thermodynamic analyses rely on accurate calorific values to estimate the potential energy release during combustion. Knowledge of the calorific value is crucial for determining the fuel efficiency of engines and assessing the overall thermodynamic performance.

Cetane Number: The cetane number is a measure of the ignition quality of biodiesel. A higher cetane number indicates better ignition characteristics. Thermodynamic studies consider the cetane number to predict combustion behaviour and optimize engine parameters for improved performance and reduced emissions.

Oxidation Stability: Biodiesel is susceptible to oxidation, leading to the formation of deposits and degradation of fuel quality. Thermodynamic analysis helps in understanding the impact of oxidation on combustion efficiency. Studying oxidation stability is crucial for developing biodiesel formulations that resist degradation over time, ensuring reliable engine performance.

Sulfur Content: Sulfur content in fuels can contribute to air pollution and corrode engine components. Thermodynamic studies consider sulfur content to assess environmental impacts and ensure compliance with emission regulations.

CHAPTER 4

EXPERIMENTAL SETUP AND METHODOLOGY

This chapter incorporates the setup used for performing experimental work. It also describes the individual component and their working which may have affected the results obtained in this analysis. The methodology opted for carrying out the detailed analysis on performance, combustion, and exergetic study have also been discussed in respective sections.

4.1 Engine Parameters

By optimizing engine design and operating parameters, improvements in internal combustion engines (IC engines) and their performance, combustion, and emissions can be achieved [114]. However, the engine design and operating parameters must be purposefully altered based on fuel qualities in order to evaluate the causes and consequences of a conventional or alternative fuel on engine characteristics [115]. In order to perform a series of experiments and gain an understanding of the process, the repercussions are perceived by manipulating each input parameter [116]. In addition to input parameters, there are a few controllable and uncontrollable elements that affect engine combustion that need to be taken into consideration [117]. Engine parameters have a substantial impact on the blend of alternative fuels since they have physicochemical qualities that are equal to those of traditional fuels [118]. The engine parameters considered as design variables and operating variables have significant impact on performance and exhaust emissions of CI engines.

4.1.1 Engine Design Variables

Combustion Chamber Design: Variations in engine design factors are more important in obtaining the best engine-out characteristics, similar to operational parameters [119]. Changing the geometry of the piston bowl improves the air-fuel mixture's mixing properties beyond the design parameters, resulting in a homogenous charge that ensures improved performance and emission characteristics [120], [121].

An engine's valve timing can be adjusted by changing the camshaft configuration [122]. Thus, an intake valve's advanced opening allows more air (oxygen) into the cylinder, improving combustion and leading to improved performance and combustion characteristics [123]. To attain maximum torque at a minimum stroke length condition, engine out torque has also been adjusted by varying the stroke length.

- **Engine compression ratio:** because of the higher compressed air–fuel mixture, enhanced compression ratio engines provide more power and are more fuel-efficient [124]. Furthermore, fuels with a strong auto-ignition characteristic can be used in engines with a high compression ratio [125].
- **Injection system:** Injection pressure and timing, nozzle holes, nozzle sac volume. variations in injection pressure result in differences in fuel atomization, with higher injection pressures enhancing atomization [126]. As a result, there is an improvement in charge homogeneity and a decrease in particulate matter and hydrocarbon emissions [127].

The air-fuel ratio and injection timing exhibit almost identical responses, with early injection promoting combustion and late injection delaying it [128]. Additionally, early injection improves charge uniformity, which reduces hydrocarbon emissions [129], [130].

- **Fuel system design:** A fuel injector's position and flow control result in a notable variation in the properties of combustion [124]. Proper placement of fuel injectors helps to ensure full combustion, which improves engine output power and reduces emissions of hydrocarbons and particulates while also preventing wall wetness and fuel impingement [125]. By wall wetting, incorrect fuel injector positioning and piston bowl shape increase unburned hydrocarbon emissions and SFC. Therefore, improved performance and emission characteristics can be achieved by modifying the shape of the piston bowl and the location of the fuel injectors . the fuel injector nozzle diameter can be changed to change the fuel flow rate [131]. Fuel with a smaller nozzle diameter has better penetration and enhances charge atomization [132]. Therefore, by effectively igniting the entire charge, optimizing spark plug location and increasing their number prevents misfiring and enhances combustion rate [133]. Multi-point fuel injection (MPFI) systems have been created in this manner to improve performance and combustion [134], [135].

4.1.2 Operating Variables

- **Exhaust Gas Recirculation:** Recirculated combustion exhaust gas provides for a low oxygen concentration in the engine cylinder, which lowers the creation of nitrogen oxides [115]. This is known as exhaust gas recirculation, or EGR, and it is a widely used technology for reducing nitrogen oxides (NOX).
- **Engine Load:** When operating load circumstances are higher and a lower compression ratio is needed to increase engine output power, performance characteristics can be improved by using engines with variable compression ratios

[124], [128], [136]. Similarly, permitting high temperatures for the intake charge intensifies combustion, improving efficiency and power production of the engine [137], [138]. Thus, achieving improved engine-out characteristics greatly depends on the optimization of engine operating parameters and the application of cutting-edge optimization techniques.

- **Engine Speed:** The increase of engine speed causes an increase in the turbulence inside the cylinder, which causes an increase in flame speed and hence, the increase in the rate of mass burning. Therefore, the time required for complete combustion is reduced and this produces higher peak pressure and temperature. Hence, higher tendency to unstable combustion. This result demonstrates the high sensitivity of the turbulent flame front speed to the engine speed, pressure and temperature inside the cylinder [139].
- **Fuel quality**: The A/F ratio has an impact on performance, combustion, and emission characteristics when it comes to operational settings. An internal combustion engine's air-fuel ratio is typically determined by the vehicle speed and demand torque, with the lean mixture being permitted under deflated torque situations and the rich mixture being permitted under inflated demand torque conditions. Greater specific fuel consumption was encouraged by the penetrated rich mixture, an unfavorable performance attribute [140]. Excessively lean and rich mixes cause significant exhaust particulate matter emissions and interfere with the phasing of combustion. Therefore, the engine-out characteristics are improved by the air-fuel ratio's optimal inflation rate [141]. The permitted rich air–fuel mixture is the reason for the increased exhaust emissions that are released under high demand torque situations. In order to

power the engine with a lean air–fuel mixture and improve fuel efficiency and emission characteristics, stratified charge near the TDC approach was devised [142].

4.2 Experimental Setup and Engine Details

A single-cylinder, four-stroke, constant speed, air-cooled, naturally aspirated, direct injection (DI), diesel engine with a rated output of 4.4 kW at 1500 rpm was used for the engine trial in all the experimental work. Appendix 1 contains the engine's technical specifications. The experimental setup's schematic layout and an image of the test engine are shown in Fig. 4.1 and 4.2 respectively. The engine was connected to an alternator that was linked to a load cell for loading purposes. The U-tube manometer along with orifice plate was used to measure air consumption for combustion [143]. A burette equipped with two optical sensors, one at a high level and the other at a low level, was used to measure the amount of fuel flow to the engine. When the liquid flow through the high level optical sensor, the sensor would give a signal to the computer to start the time, and once the fuel reached the lower level optical sensor, the sensor would give a signal to the computer to stop the time and refill the burette. The time spent for the fuel consumption was noted. A K type (Chromel-Aluminium) thermocouple coupled to a digital indicator was used to measure the temperature of the exhaust gas from the engine [144]. For the purpose of measuring cylinder pressure, a piezoelectric pressure transducer of the Kistler type was installed on the cylinder head. The engine crank angle is measured using a 11-bit, 2050 step crank angle encoder installed on the crankshaft. The engine crank angle was measured using a crank angle encoder with a top dead center (TDC) marker [145].

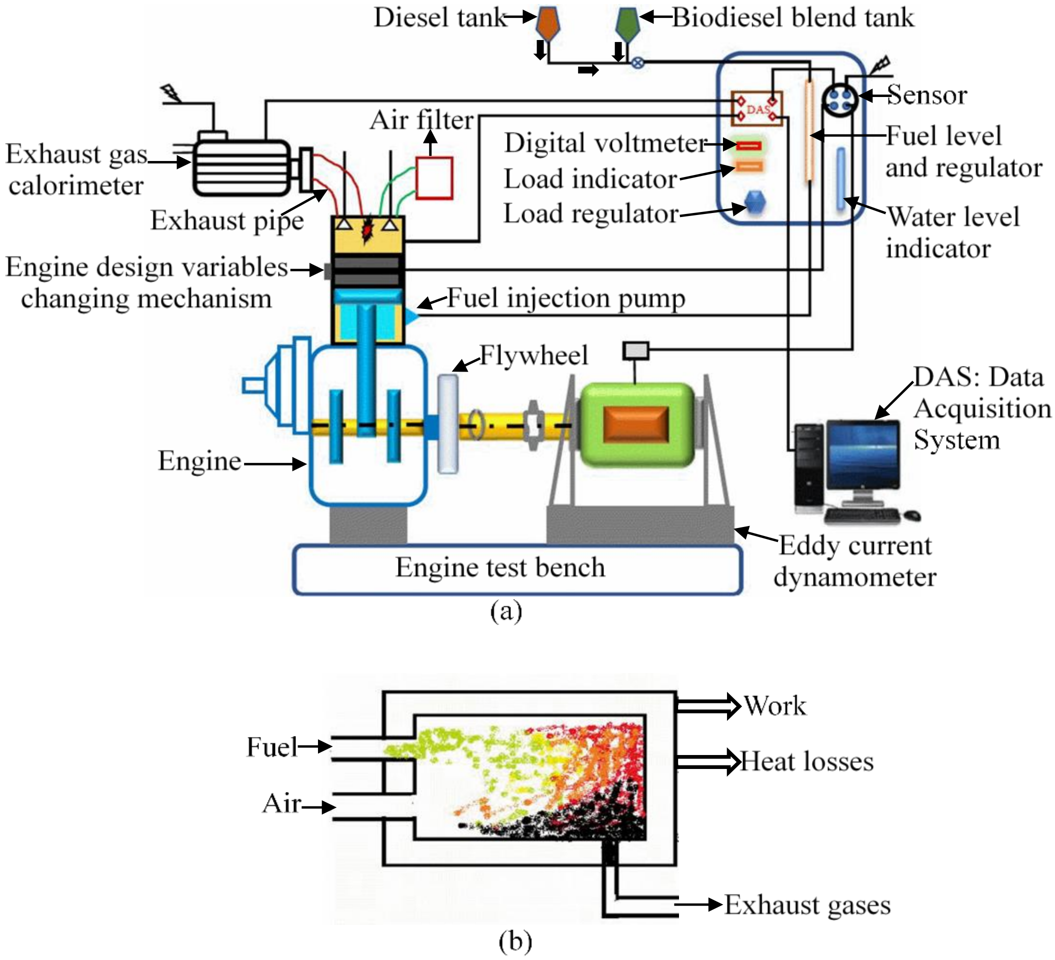


Fig. 4.1 Schematic layout of the experimental setup and control volume

A control panel that was connected to the engine setup was equipped with the ability to communicate with the pressure sensor and convert the pressure sensor's signal to an analogue voltage signal, which was then provided to the data acquisition system (DAS). AVL DiGas 444 exhaust gas analyzer was used to test the exhaust gas chemicals including CO, CO_2, HC, NO, and O_2 .

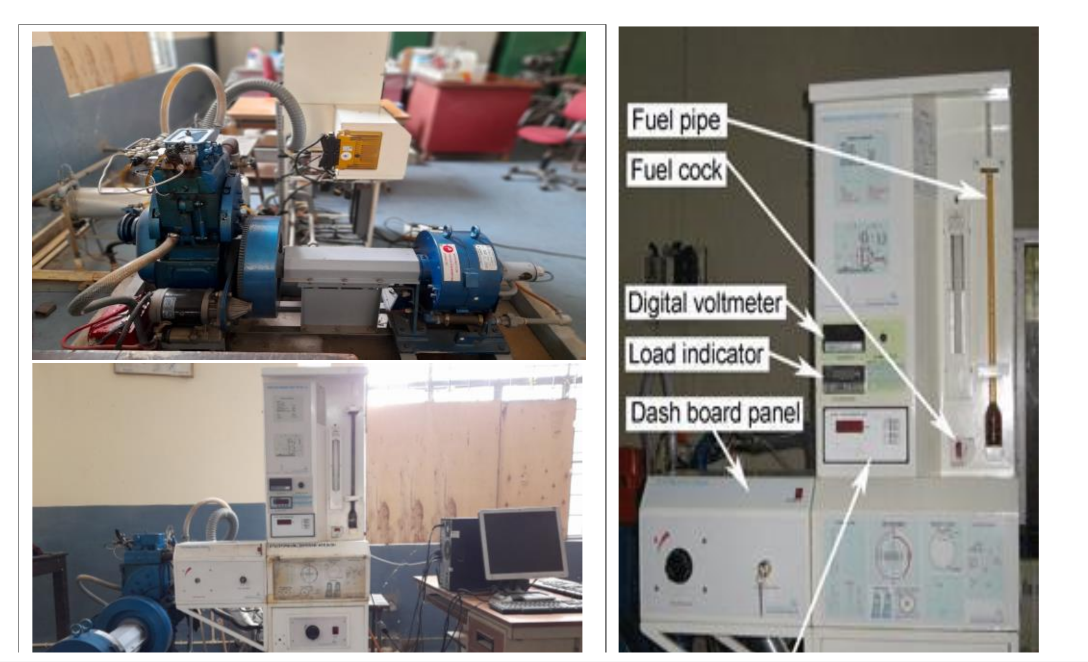


Fig. 4.2 Photographic view of the test engine

An AVL 437 diesel smoke meter was used to evaluate the exhaust gas's smoke content. In the next subsections, each component or instrument used in the research investigation is detailed in detail. The data acquisition system received as inputs the amount of time needed for fuel to fuel, the heating value, and the fuel density. The data acquisition system (DAS) uses an excel sheet that is provided to determine engine metrics like fuel consumption and brake thermal efficiency.

Table 4.1 Specifications of Engine

Product	CRDI VCR Engine test
Engine	Make Kirloskar, Four stroke, Single cylinder, water cooled, Power 3.5 kW at 1500 rpm, Bore 87.5 mm, Stroke 110 mm, Capacity 661 cc.
VCR arrangement	CR range 12-18
Dynamometer	Type eddy current, water cooled with loading unit
Propeller shaft	With universal joints
ECU Model	Nira i7r (with solenoid injector driver) with programmable ECU software and Calibration cable

Data Acquisition Device	Make NI Instrument USA, NI USB-6210, 16-bit, 250kS/s.
Air box	M S fabricated with orifice meter and manometer
Air flow transmitter	Make Wika Germany, Pressure transmitter, Range (-) 250 mm WC
Injector	Type Solenoid driven
Fuel tank	Capacity 15 L, Type: Duel compartment, with glass fuel metering pipe (column)
Common rail	With pressor sensor and pressure regulating valve
Calorimeter	Type Pipe in pipe
Piezo sensor	Make PCB USA; Combustion: Range 350 Nar with low noise cable
Crank angle sensor	Make Kubler Germany, Resolution 1 Deg., Speed 5500 rpm with TDC pulse
Digital millivoltmeter	Range 0-200mV, panel mounted
Temperature sensor	Make Radix, Type RTD, PT100 and Thermocouple, Type K
Temperature transmitter	Make ABUSTEK USA, Type two wire, Input RTD PT100, Range 0–100 °C, Output 4-20 mA and Type two wire, In-put Thermocouple.
Load indicator	Digital, Range 0-50 Kg, Supply 230V AC supply
Load sensor	Make VPG Sensotronics, Load cell, type strain gauge, range 0-50 Kg
Fuel flow transmitter	Make Yokogawa Japan, DP transmitter, range 0-500 mm WC
Software	“ICEngineSoft” Engine performance analysis software
Rotameter	Make Eureka, Engine cooling 40-400 LPH; Calorimeter 25-250 LPH
Pump	Make Kirloskar, Type Monoblock
Overall dimensions	W 2000 x D 2500 x H 1500 mm

Additional	Computerized injection pressure application and measurement

For loading purposes, the engine was connected to an alternator that is connected to a load cell as shown in Fig. 3.3. The field current and field strength are induced as the alternator's armature rotates by the engine, and this has the tendency to drag the field coils and casing along with it. The same method used with the hydraulic dynamometer can be used to counteract this spin. The banks of electrical resistances typically dissipate this produced field strength as heat.

Fig.4.3 Photographic view of the eddy current dynamometer

By turning On or Off the load resistances in the load cell bank and changing the field strength, the load, and speed on the alternator and therefore on the engine can be changed. An increase in power enables the engine to beat the alternator's resistance and keep the engine controller's preset speed. Optical sensors and DAS were used to measure fuel use. The outlet of the solenoid valve was attached to a glass burette, and the same was connected to the engine by a manual ball valve. The fuel from the reservoir was connected to the solenoid valve. The glass burette is depicted in Fig. 4.4. The amount of fuel flow to the engine was measured using a burette that had two optical sensors, one at a high level and the other at a low level. When liquid passed through the high level optical sensor, the computer received a signal to begin keeping time. The computer would receive a signal to halt the timer and replenish the burette once the gasoline reached the lower level optical sensor. It was timed to see how long it took to consume a certain amount of fuel. The manual measurement of fuel consumption is also possible with the use of a digital stopwatch and burette.

The cubical air tank served as a conduit for the air flow to the engine. The air tank accomplishes its goal of controlling the airflow into the tank. A U-tube manometer attached to an aperture mounted on an air box in the suction was utilized to measure the intake air flow rate because the air tank's inlet was equipped with one. The surge tank was attached to the other end of the manometer, which had one end left open to ambient temperature [146]. In order to determine the water head in terms of the pressure differential, it provided a reading for the difference in the water level between two columns [147].

With the aid of a K-type thermocouple installed in the exhaust pipe, the temperature of the exhaust gas was measured [148], [149]. Two distinct wires are heated to the same temperature in thermocouples, and when the two wires are linked, a voltage is produced that may be related to temperature. Nickel and chromium or aluminum are the materials used for the wire set in K-type thermocouples.

Since cylinder pressure affects the engine's performance metrics and pollution levels, the cylinder pressure crank angle diagram is used to analyze the combustion behavior of the engine. A quartz piezo-electric transducer (model 5395A) developed by Kistler was used in this investigation to monitor the in-cylinder gas pressure in conjunction with a Kistler charge amplifier positioned on the test engine's cylinder head. A photographic view of the Kistler pressure transducer is shown in Figure 4.4. Piezoelectricity, as the name implies, is electricity produced by pressure. It's Greek in origin. Amber, an early source of electric charge, is represented by the Greek word piezo, which meaning to press or squeeze. The direct outcome of the piezoelectric effect is piezoelectricity. Appendix 2 contains the pressure transducer's specifications. A reliable integrated high temperature Viton cable was used to connect the sensor to the charge amplifier, which changed the electric charge produced by the piezoelectric pressure sensor into voltages that could be used with standard measurement and data recording tools.

Over a period of time, the data showed good linearity and repeatability. Since the sealing was done at the adapter's shoulder, the area needed to be level and smoothly machined. The charge amplifier has a range of 0-100 bar and a power supply voltage of 7-32 VDC (40 mV/brand operates with a time constant of 5 s). The photographic image of the pressure transducer installed on the cylinder head is shown in Figure 4.5.

Fig. 4.5 Photographic view of the pressure transducer mounted on the engine head.

4.3 Experimental Procedures

The engines was initially started with diesel fuel, and the trials were carried out with the engine manufacturer's recommended initial injection timing of 23 CA bTDC, nozzle opening pressure of 200 bar, and compression ratio of 17.5 to acquire the reference data. Additionally, the engine was operated under the same conditions while using Tallow biodiesel. For both test fuels, the engine was ran at no load, 25%. 50%, 75%, and 100% loads. All combustion, performance, and emission characteristics were measured throughout each test. Tests were then undertaken using various combinations of mineral Diesel and tallow biodiesel to examine the impact of the blend on the engine's combustion, performance, and emission characteristics [150]. On a volume basis, the blend's tallow biodiesel content was adjusted from 10% to 30% at regular intervals of 10%. The blends were designated as B10, B20, and B30; where the numerical value denotes the amount of tallow biodiesel in each mix of diesel and tallow biodiesel. All the readings were recorded after the engine had stabilized. To remove the test fuel from the fuel line and the injection systems, the fuel was changed back to diesel after each blend test and the engine was left running for at least 15 minutes before moving on to the next blend. The results of each test were repeated three times to ensure their consistency. The averages of these outcomes form the values provided in this study. To guarantee the repeatability of the findings, each test was carried out three times before being averaged.

4.4 Selection of Engine Test Parameters for Thermodynamic Study

According to reports, there are numerous ways to enhance engine performance, including raising the compression ratio, the nozzle opening pressure, and the fuel injection timing. It was observed that conventional diesel engine are only intended to run on diesel fuel, numerous studies have reported on the ideal design parameters for diesel engines when running on alternative fuels [151]. The effects of changing the injection timing, nozzle opening pressure, and compression ratio on the thermal efficiency, specific fuel consumption (SFC), and exhaust emissions of CI engine have been the subject of several studies [152]. Some studies were conducted on a diesel engine at various nozzle opening pressures and an optimal injection timing of 24.5 CA bTDC. These studies discovered that the engine's overall performance was enhanced by an advanced injection timing of 24.5 CA bTDC and a greater nozzle opening pressure of 220 bar.

4.4.1 Variation of compression ratio

Because of the rise in the pressure and temperature of the compressed mixture in the combustion chamber, which causes a rise in the peak cylinder pressure and the fuel-air combination's burning speed, using a greater compression ratio typically improves the density of the fuel-air mixture. An experiment was conducted to examine the effects of running the blend-fueled engine at two additional compression ratios, one higher (18) and one lower (15), in addition to the original compression ratio of 17.5 while maintaining the engine's injection timing and nozzle opening pressure at optimal levels. Experimental trials were carried out utilizing the tallow biodiesel blend for the compression ratios of 15, 16, 17, 17.5, and 18 with an advanced injection timing of 24.5 CA and a higher nozzle opening pressure of 220 bar. Poor performance was the result of compression ratios below 15 and, because of structural limitations in the engine, it was limited till a compression ratio of 18. By adjusting the clearance volume and swapping out the gaskets between the cylinder and the cylinder head for ones of a different thickness, the engine's compression ratio was changed. The photographic view of the compression ratio changing mechanism on the cylinder block is shown in Figure 4.5. Compression Ratio adjustment was done by following steps:

- Slightly loosen 6 Allen bolts provided for clamping the tilting block.
- Loosen the lock nut on the adjuster and rotate the adjuster so that the compression ratio is set to “maximum”. Refer the marking on the CR indicator.
- Lock the adjuster by the lock nut.
- Tighten all the 6 Allen bolts gently.
- The centre distance between two pivot pins of the CR indicator can be measured and noted to verify the Compression ratio attained.
- After changing the compression ratio the difference (Δx) can be used to know new CR.

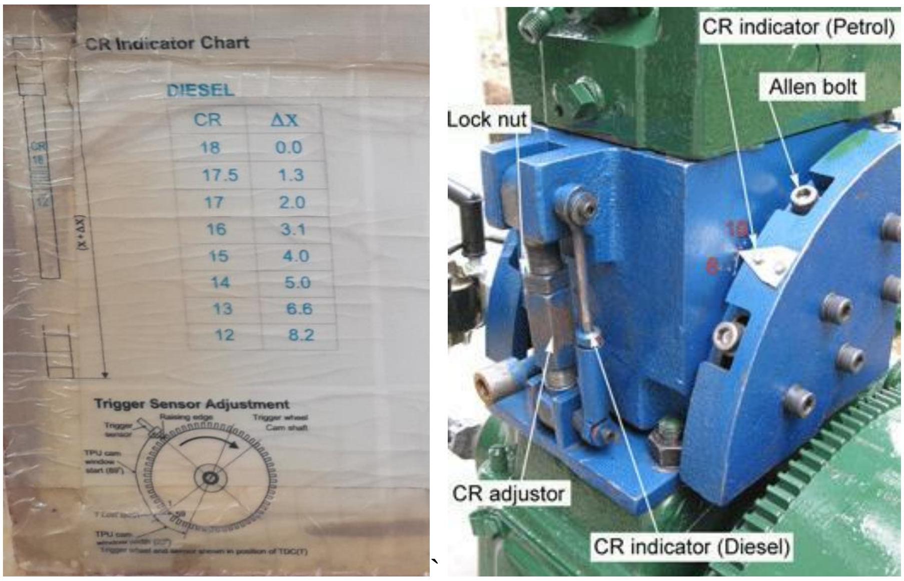


Fig. 4.4 Compression ratio changing mechanism on cylinder block

4.4.2 Variation of Injection Pressure

CI engines are often made to run exclusively on diesel. Certain engine operating parameters must be optimized for alternative fuels in light of their combustion, performance, and emission characteristics. It's crucial to remember that the fuel-air combination fed to a diesel engine has a major impact on how the engine behaves [153]. The fuel injection rate, injection time, and nozzle geometry all affect how much fuel is combusted. Additionally, because of the large changes in temperature and pressure that occur as the piston approaches top dead center, injection timing is crucial to the performance and emission characteristics of a diesel engine [154]. Further experiments were carried out in this context for the ideal blend, B20 at various injection timings. The fuel pump was disassembled in order to alter the injection timing before conducting this experiment. By changing the number of shims installed under the plunger in the pump, either by adding or removing shims, the initial injection timing was changed. The initial injection timing of 23 CA bTDC (as defined by the engine manufacturer) was used in trials utilizing diesel and tallow biodiesel blend to get the experimental data.

4.5 Energy and Exergy Analysis

Exergy is referred to as the useful component of matter or energy. It is also considered as energy's quality, where quality is defined as the capacity to carry out useful work which can be compared to the lifting a weight [155]. Exergy can be interpreted in terms of quality or utility, although this can sometimes be confusing because quality and usefulness are intensive concepts, whereas exergy is formally an extensive one. The second law of thermodynamics gave rise to the thermodynamic concept of exergy [156]. There are various definitions of exergy that all cover the same fundamental concept, but they differ in how explicitly they state the derivation assumptions. The definition of exergy in this thesis is based Wall ‘s (1977)

Work, which Corneissan and Valero also confirms in their dissertation on exergy that the quantity of mechanical work that may be maximally extracted from a system in a given environment is known as its exergy [155]. Three characteristics of exergy must be briefly discussed before advancing the connection between exergy and resource use. Exergy has these three benefits above other thermodynamic notions, notably energy, according to widespread understanding. Although the validity of these three claims will be thoroughly addressed in this thesis, they offer a preliminary defense for the use of exergy. However, it should be noted that the assertions stated on the general qualities do not represent the thesis’s conclusions; rather, they serve as an explanation of why exergy is worthwhile to investigate further.

No exergy is available to the system that is in thermodynamic equilibrium with a reference environment. As a result, while the reference environment is in internal stable equilibrium, it might not itself be a source of exergy. Exergy can only be destroyed (or conserved in a reversible process), whereas energy can never be created or destroyed. Since exergy is a term derived from the second rule of thermodynamics, it is not conserved. The Guoy-stodola theorem provides the clearest explanation of the relationship as shown below:

$$B_{destroyed} = T_o S_{gen}$$

Where, $B_{destroyed}$ is exergy destroyed, T_o is the temperature of the reference environment, and S_{gen} is the amount of entropy produced. The claim that resource consumption cannot be accurately quantified using matter or energy since both are preserved is the starting point of the exergy argument. Exergy proponents point out that resource consumption is actually equivalent to the deterioration of the resource quality in order to assess how the significant elements of a resource change throughout consumption. To put it in other way, the exergy destruction of a resource is a measurement of how much of its value is used, and the exergy of a resource is a measurement of its value.

Exergy appears to be the foundation for the use of energy as a metric for resource use. Exergy must be adopted as a measure of resource valuation and resource, thus there must be a good cause to re-examine the subject. The need for self-reflexive study on exergy theory and the fact the exergy theory is already showing certain flaws are the two main justifications for reconsidering the fundamental relationship between exergy and resources.

4.5.1 First and Second Law Theoretical Considerations

Usually, energy analysis is about energy flow through the system, i.e., energy inflows, outflows, and absorption. From a general perspective, heat is input to the system, work obtained is the desired output, and the rest of the energy is released in different forms of energy. In thermodynamics, the study is focused on the system, and the system has to be well-defined by boundaries. For the present study, the schematic diagram of the engine setup as shown in Fig. 1(a) and control volume depicted in Fig. 1(b), was taken as a system in which energy flow has been shown. This thermodynamic study was done to test tallow biodiesel under different operating conditions [27]. Impacts of different variables, such as the use of blended fuel, differing compression ratio, varying engine load, and so on, help to quantify losses during experimentation. The engine's input parameters were air and fuel; while work, heat loss to coolant, heat loss to ambient, and exhaust gases are the output parameters. The following assumptions have been made to simplify and apply it suitably for the considered control volume [157]:

- Steady-state condition for engine operation.
- Intake air is an ideal gas.
- Ignoring the energy rate of combustion air.
- Due to its negligible value, kinetic and potential energy values were ignored.
- An analysis is done for control volume considering the entire engine.
- For all the calculations, wherever necessary, a lower heating value of the fuel was used.

All the equations used for the thermodynamic analysis are presented below and are based on the above assumptions.

Heat energy supplied by fuel is given by Eq. (1),

$$\dot{Q}_{in} = \left[\dot{m}_f \times LHV\right], kW \tag{1}$$

where, $\dot{Q}_{in}$ is heat energy supplied by fuel (kW), $\dot{m}_f$ is mass of fuel consumed (kg/s), LHV is lower calorific value (kWh/Nm^3). The rate of heat input is also fuel energy input and obtained from equation (1).

The power output of the engine or shaft power is given by

$$\dot{Q}_s = BP = \left[\frac{2\pi \times N \times W \times r}{60 \times 100}\right], kW \tag{2}$$

where, N stands for speed of the flywheel, W is load applied to engine (kgf) and r is drum radius (m).

Heat rate carried away by cooling water is given by

$$\dot{Q}_W = \dot{m}_w \times C_{pw} \times (T_2 - T_1) \tag{3}$$

where, $\dot{m}_w$ water flow through pump (Kg/s), C_{pw} is specific heat capacity of water (kJ kg^{-1}K^{-1}) and T is temperature with subscript $_2$ for outlet and $_1$ for inlet to engine (K).

The energy transferred to the atmosphere or available energy of exhaust is given by

$$\dot{Q}_E = \dot{m}_E \times C_{pE} \times (T_E - T_A) \quad (4)$$

where, $\dot{m}_E$ is mass from engine exhaust and is sum of $\dot{m}_a$ and $\dot{m}_g$ (Kg/s), C_{pE} is specific heat capacity of exhaust gas (kJ $kg^{-1}K^{-1}$), T is temperature with subscript $_E$ for exhaust and $_A$ for ambient (K).

Specific heat of exhaust is evaluated by equating heat carried away by the calorimeter to the heat lost by exhaust gases and is given by

$$C_{pe} = \frac{[\dot{m}_{cw} \times C_{pw} \times (T_{cwo} - T_{cwi})]}{[(\dot{m}_a + \dot{m}_f) \times (T_{eci} - T_{eco})]}, \quad (5)$$

Unaccounted losses include heat transfer to the cylinder wall and the amount is given by

$$\frac{d\dot{Q}_{wall}}{d\theta} = A \times h_{conv} \times (T_E - T_W) \quad (6)$$

where, h_{conv} is convective heat transfer coefficient, T is temperature with subscript $_E$ for engine exhaust gas an $_W$ for cylinder wall.

Brake thermal efficiency and brake specific energy consumption is given by Eq. (7) and (8) respectively,

$$BTE = \left[\frac{\text{BP} \times 3600 \times 100}{\dot{Q}\text{in}}\right] \quad (7)$$

$$BSFC = \left[\frac{\dot{m}_f \times LHV}{BP}\right] kJs^{-1}kW^{-1} \quad (8)$$

For the control volume defined in Fig. 2, mass balance is given by Eq. (9),

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (9)$$

where, ṁ is mass flow rate with subscript $_{in}$ for inlet and $_{out}$ for outlet (Kg/s).

Similarly, energy balance for the control volume defined in steady-state conditions is

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \quad (10)$$

Where $\dot{Q}$ is heat transfer rate (kJ) and $\dot{W}$ is rate of work done through system considered (kJ), h is the specific enthalpy with subscript $_{out}$ for outlet and $_{in}$ for inlet (kJ/kg).

For any exergy analysis, defining the reference dead state for establishing equilibrium with the environment and was taken at pressure (P_0) and temperature (T_0) as 1.10325 bar and 298.15 K respectively [30]. In thermodynamics, the term exergy is the maximum useful energy obtained from any system [31]. Calculations of exergy are based upon the second law of thermodynamics. The exergy of particular fuel during the combustion process can be estimated by summing up the exergy through shaft, cooling water, exhaust gases, unaccounted losses (heat lost to surroundings), etc; exergy rate through which was quantified numerically by following equations:

$$E°_{in} = \left[\frac{1.038 \times \dot{m}_f \times LHV}{3600}\right], kW \quad (11)$$

$$\frac{dE°_s}{d\theta} = \int\left(\frac{dV}{d\theta}\right) \times (P - P_0) \quad (12)$$

$$E°_w = \left[Q_w - \left\{\dot{m}_w \times C_{pw} \times T_A \times \ln\left(\frac{T_{ewo}}{T_{ewi}}\right)\right\}\right], kW \quad (13)$$

$$E°_e = Q_e + \left[(\dot{m}_a + \dot{m}_f) \times T_{amb} \times \left\{C_{pe} \times \ln\left(\frac{T_A}{T_{eci}}\right) - R_e \times \ln\left(\frac{P_A}{P_e}\right)\right\}\right], kW \quad (14)$$

After considering all the parameters, the exergy rate balance and its exergy rate destruction are given by

$$E°_{in} = [E°_d + E°_s + E°_w + E°_e], kW \quad (15)$$

$$E°_d = [E°_{in} - (E°_s + E°_w + E°_e)], kW \quad (16)$$

where, $E°_{in}$ is for fuel input, $E°_s$ is for shaft, $E°_w$ is for cooling water, $E°_e$ is for exhaust gas exergy and $E°_d$ is destruction in exergy.

Obtaining information regarding improved system performance is done by assessing useful energy and finding exergy efficiency. The recoverable exergy to the total exergy of the system is found by eq. (16) and is called the second law efficiency or exergy efficiency.

$$\eta_{II} = \left[1 - \left(\frac{E°_d}{E°_{in}}\right)\right] \times 100\% \quad (17)$$

4.6 Exergy for a fuel [158]

The heating value and specific heat of a fuel determine its energy content. Using the fuel's higher heating value and specific heat, exergy has been computed as following equation.

$$\varepsilon_f = h_f - T_o s_f \quad (18)$$

Exergy of fuel (i.e., hydrocarbon) is equivalent to chemical exergy of fuel, which can be determined, at ambient circumstances by using equation equation (18).

$$\varepsilon_{ff} = \gamma_{ff} H_{ff} \quad (19)$$

Typically, the fuel's chemical exergy at ambient pressure and temperature corresponds to the fuel's higher heating value. Flue gas and hot product (gases in the combustion chamber) are mixtures of several gases. The partial molar characteristics are used to compute the enthalpy and entropy of a mixture.

It is possible to write out the mathematical equation for the mixture's enthalpy and entropy as equations 20 and 21:

$$h = \sum N_i h_i \tag{20}$$

$$s = \sum N_i s_i \tag{21}$$

The equation for the energy and exergy balance of an unsteady flow process over a finite time period is written as equation 22 and 23 :

$$Energy\ input - Energy\ output = Energy\ accumulation \tag{22}$$

$$Exergy\ input - Exergy\ output - Exergy\ consumption = Exergy\ accumulation \tag{23}$$

4.7 Instrument Accuracy and Uncertainty Analysis

In the calibration process, the relationship between the measured and accurate values is established by comparing the sensor's output signal to the value measured by an accurate device. To prevent measurement mistake, the pressure transducer was periodically calibrated. A dynamic calibration method was performed on the Kistler model 5395A piezoelectric transducer utilizing a conventional dead weight tester. With a piston whose cross-sectional area precisely measured, the dead weight tester hydraulically lifted precise weights to produce the specified pressure. These transducer's charge output signal was fed through a high impedance cable as input of a charge amplifier.

The low-level charge, which is on the order of few Pico-Coulombs, is converted by the charge amplifier into a proportional voltage that can be recorded using common data gathering tools. In this process, the transducer was subjected to a known pressure. The output was then grounded to zero volts, which stopped signal degradation. The weights were then quickly released from the hydraulic pressure holding them aloft, causing the pressure to drop abruptly to air pressure.

A digital oscilloscope set up to trigger on a voltage drop was used to record the voltage change as a function of time. A peak-to-peak computation tool on the scope was utilized to determine the voltage shift brought on by the pressure change. From 200 to 1000 psi, dynamic pressure measurements were taken at 200 psi intervals. At each dynamic pressure, ten readings were made. Following an average calculation, these were plotted against the corresponding voltage output. The transducer's linearity was discovered to be better than 1%. About 2 to 3% repeatability was found to exist.

The pressure transducer's electrical charge output was changed into proportional voltage using the charge amplifier. It was made up of an operational amplifier that provided feedback through a variable capacitor that could be altered depending on the range chosen. The output voltage is the integral of the change variation, and this combination served as an integrator for the current inputs from the transducer. The overall charge at any one time was directly proportional to this voltage output. The charge amplifier was given four hours to warm up before the measurements were made in order to ensure the precision of the pressure measurement. Appendix 3 contains the charge amplifier's specifications.

The analog to digital converter (ADC) stores the information about a real system in a way that it makes it simple to access the data for scientific evaluation and analysis. The information in ADC should be captured automatically or without direct human assistance and direction. Different engine operating parameters, such as instantaneous pressure, crank angle, ignition delay, heat release rate, brake thermal efficiency, fuel consumption, and exhaust gas temperature, were analyzed using the DAS graphical analysis, as well as the differential equation was evaluated and the mathematical expression was computed. Display, control, and recording of the results ere also performed. The data was processed and stored on a computer for the duration of the study.

All the measurements taken during experimentation in IC engine relating to crank angle are based on the crank angle encoder. On the engine's camshaft, an 11 bit 2050 step crank angle encoder was installed to track the crankshaft's angular position. To sense the position of top dead center, a crank angle encoder with a TDC marker was employed. Figure 4.6 displays the photographic view of TDC marking. It is a high precision optical pickup equipment for torsional investigation of IC engines with a pulse count of 360 ppr (pulse per rotation). A charge amplifier was wired up to the output of the crank angle encoder and pressure transducer. The output signal from the charge amplifier was sent to a computer via an ADC. The analog single was transformed into digital impulses at set crank angles in this system. The computer then received the digital signal and stored it there. A data acquisition system (DAS) was used to handle, analyze, and display all of the sensor data. The experiment's overall uncertainty was estimated by adding the uncertainties of each instrument, and the results are shown below:

Total percentage of uncertainty of this experiment is =

$$\sqrt{\begin{matrix}(Total\ Fuel\ Consumption)^2 + (Brake\ Power)^2 + \\ (Specific\ Fuel\ Consumption)^2 + (Brake\ Thermal\ Efficiency)^2 + \\ (CO)^2 + (NO)^2 + (Pressure\ Transducer)^2 + \\ (EGT)^2\end{matrix}} \quad (24)$$

$$= \sqrt{(1.5)^2 + (0.2)^2 + (1)^2 + (1)^2 + (0.2)^2 + (0.2)^2 + (0.2)^2 + (0.05)^2 + (1)^2 + (0.15)^2}$$

=±2.33.

Thus, the total uncertainty for the whole experimentation was found to be ±2.33.

CHAPTER 5

RESULTS AND DISCUSSION

The thermodynamic analysis of combustion of biodiesel fuelled engines is meant to assess and compare the various combustion process and systems rationally and eloquently. This review paper briefly described the different ways for estimating the effectiveness of combustion in biodiesel fuelled ci engine adopted by researchers and then comprehensively summarized experimental analysis, fuel considered, and corresponding performance evaluation (especially exergy output). Exergy analysis provides insights into the areas where energy losses occur and helps in optimizing the design and operation of the engine to improve efficiency. It is a valuable tool for understanding the thermodynamic performance of biodiesel-based CI engines and identifying opportunities for improvement in terms of energy utilization.

5.1. Combustion Parameters

Following sections present an insight to the combustion analysis of tallow biodiesel fueled compression ignition engine.

5.1.1 Cylinder Pressure

The fuel fraction burned in the premixed burning phases of a compression ignition engine determines the peak cylinder pressure, or the pressure created in the early stage of combustion. The fuel's capacity to combine properly with air and ignite will dictate the cylinder pressure [159]. The difference in in-cylinder pressure between diesel and biodiesel when blended at 10%, 20%, and 30% with the engine operating at 1500 rpm., in the experiment, diesel fuel and its mixes' cylinder pressure patterns are comparable to those of biodiesel [160]. A p-V diagram, which depicts a system's pressure as a function of volume, is used to determine work done and to comprehend how pressure directly impacts volume. It is clear from n figure 5.1 that diesel fuel has larger peak cylinder pressure than biodiesel mixes do. The peak cylinder pressure of diesel fuel is 45.91 bar at high engine load at 1500 rpm, compared to 45.65 bar for B10, 45.16 bar for B20, and 43.80 bar for B30 biodiesel mixes. For B10, B20, and B30, the values varied by around 0.6%, 1.6%, and 4.6%, respectively.

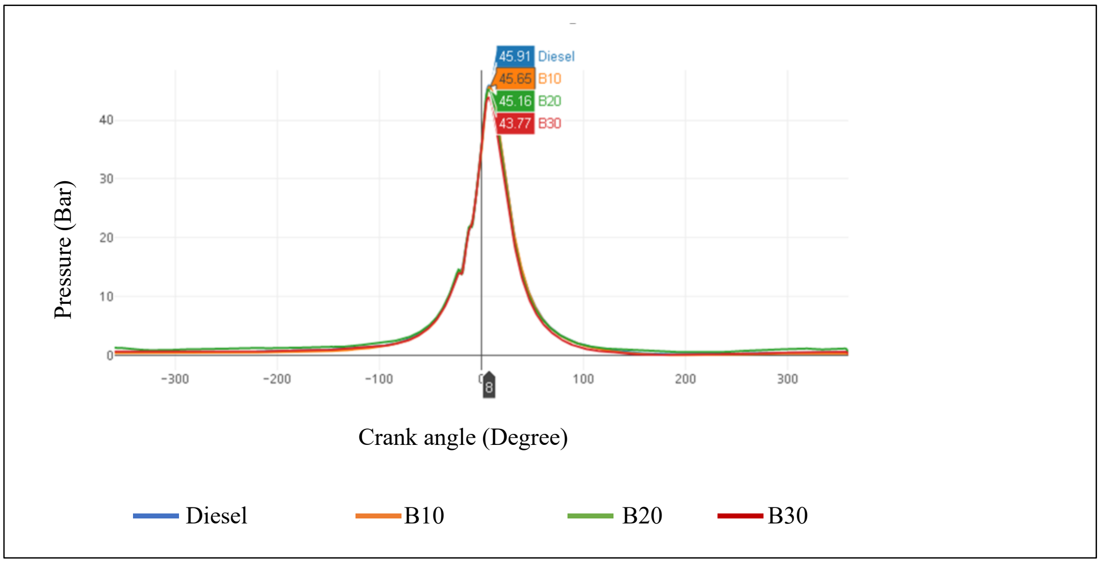


Fig. 5.1 Pressure vs. Crank angle graph

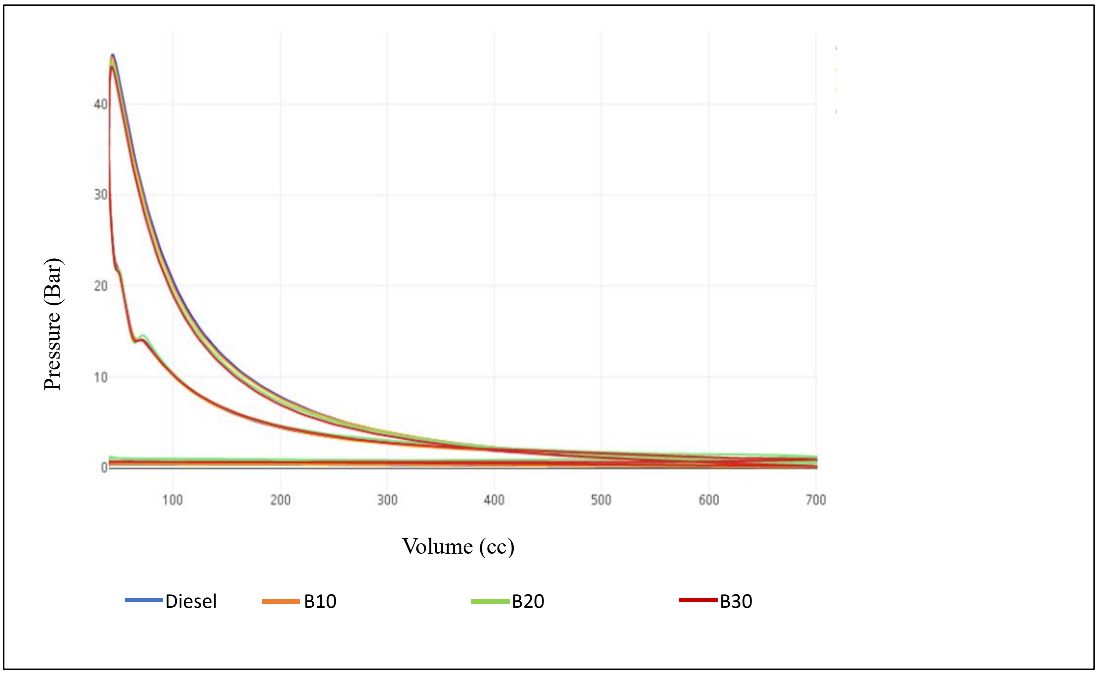


Fig. 5.2 Pressure vs. Volume graph

The p-v diagram for mixtures of diesel and biodiesel is shown in Fig. 5.2, which shows that the maximum area under the curve, which represents the maximum work production under the operating conditions, is surrounded by diesel fuel. Midway during the compression and expansion strokes, there are small variations in the p-v curve. The graph demonstrates that small variations for various blending ratios exist. This demonstrates how combustion-related factors make up for the decreased heating value of biodiesel.

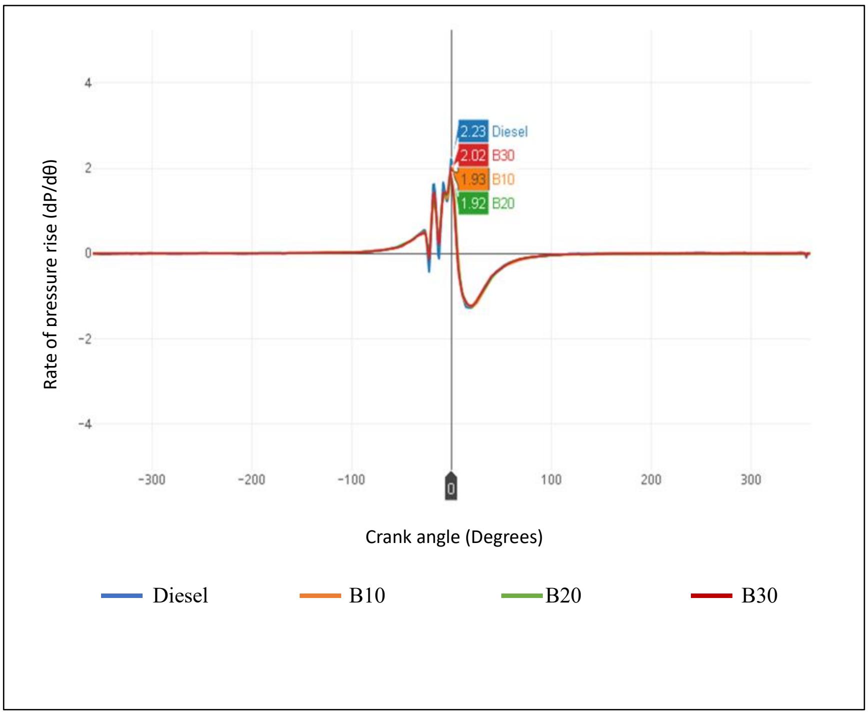


Fig. 5.3 Rate of pressure rise vs. crank angle

5.1.2 Maximum Rate of Pressure Rise

Fig. 5.3 depicts the rate of pressure rise variation for diesel and biodiesel mixes with an engine running continuously at 1500 rpm. At maximum engine load, the peak pressure rise for diesel fuel is 2.23 bar/deg, while it is 1.93 bar/deg (B10), 1.92 bar/deg (B20), and 2.02 bar/deg (B30) for biodiesel. Diesel fuel has a greater peak pressure during combustion because the ignition delay causes combustion to begin before the TDC, which causes heat to escape more quickly during premixed burning.

5.1.3 Heat release rate

Fig.5.4 illustrates the variance in heat release rate for diesel and biodiesel blends with blending percentages of 10%, 20%, and 30% when the engine is operating at a constant 1500 rpm. It is evident that there is a negative heat emission at first. Due to the buildup of fuel, which causes vaporization, a phenomenon in which heat is absorbed and therefore results in negative heat release, as well as the endothermic nature of the chemical and physical processes that take place during the ignition delay period, negative heat is produced. The phases of combustion for biodiesel and diesel are the same. Following the ignition delay phase, the fuel-air combination burns quickly in the premixed combustion stage, followed by the diffusion combustion stage, amnd when auto-ignition takes place, the heat release turns positive. In this phase, the fuel-air mixing velocity governs the burn rate. Due to a reduced ignition delay, combustion might be seen to begin earlier for biodiesel mixes. Diesel fuel releases heat at a maximum rate of 21.93 J/deg, whereas biodiesel releases heat at rates of 20.62 J/deg (B10), 21.21 J/deg (B20), and 18.63 J/deg (B30). Due to its increased volatility and easier mixing with air, diesel fuel has a slightly higher peak heat release rate than biodiesel mixes. Longer diesel fuel ignition delays may also contribute to increased peak heat release rates by causing significant amounts of fuel to accumulate in the combustion chamber during the premixed burning phase [161].

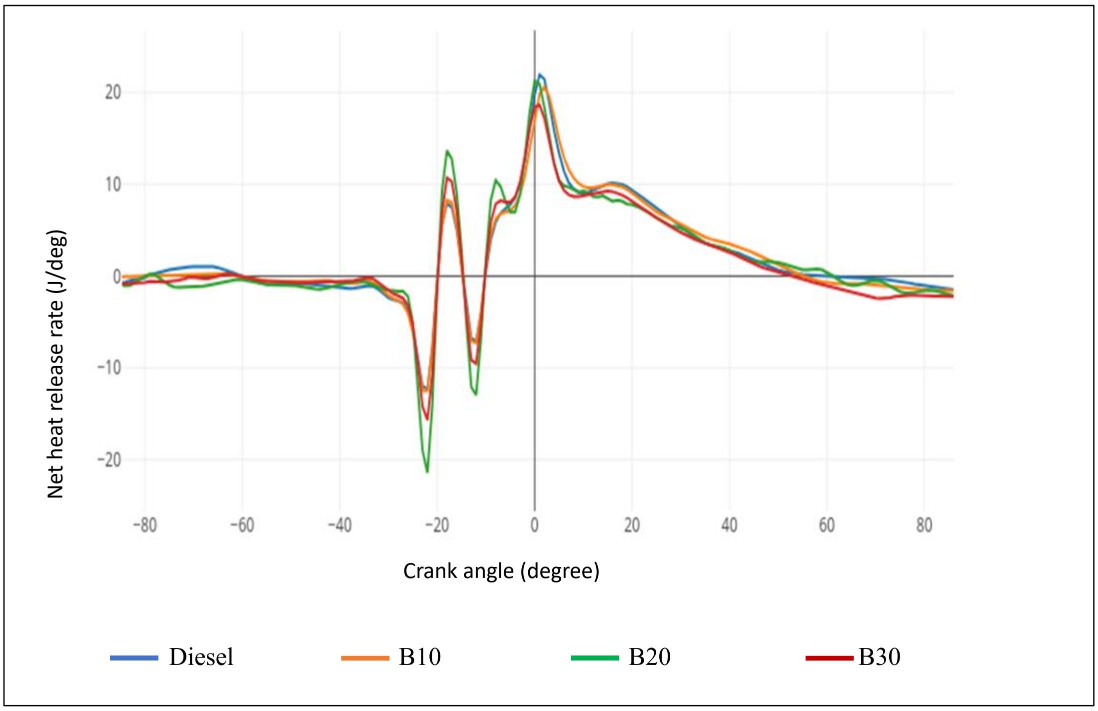


Fig. 5.4 Net heat release rate vs. crank angle

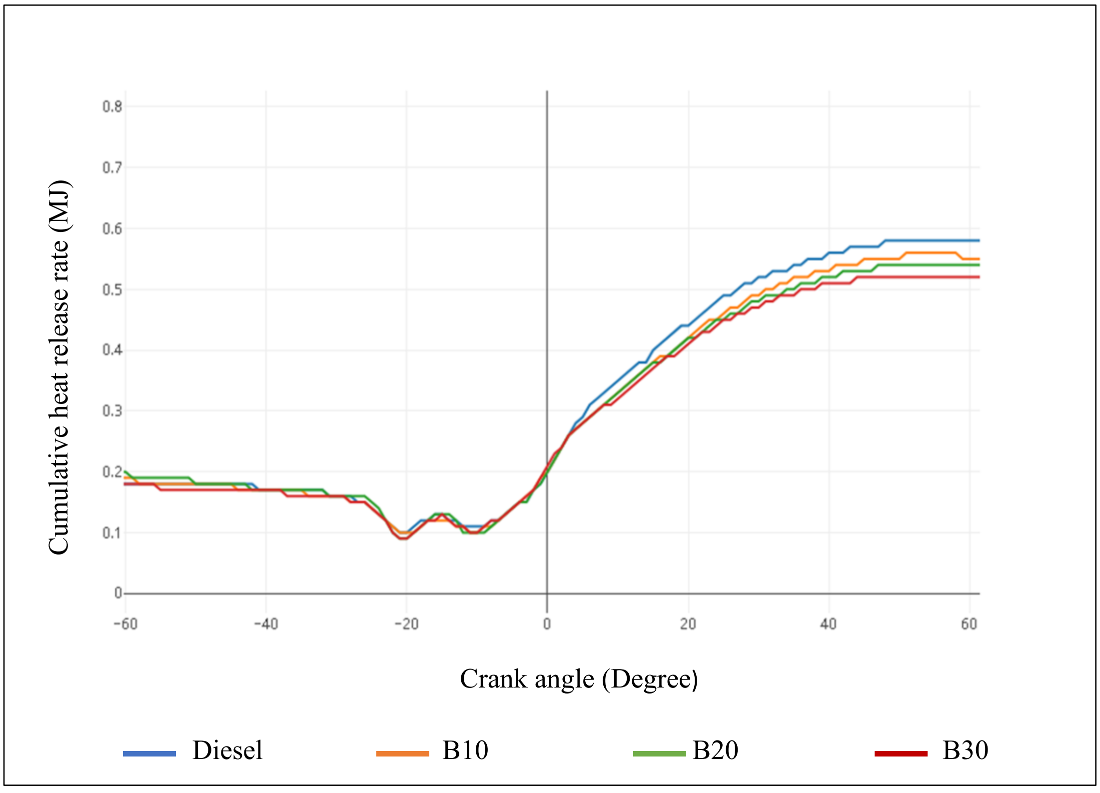


Fig. 5.5 Cumulative heat release rate vs. crank angle

However, with biodiesel mixes, the heat releases during the late combustion phases is just slightly lower than that of diesel. This is so that the fuel that is left over from the primary combustion phases and the last to burn in the later combustion phases can burn completely thanks to the components with greater oxygen concentration.

5.1.4 Cumulative Heat Release Rate

Fig. 5.5 displays the cumulative heat release rate variation of diesel and biodiesel mixes. Diesel fuel has a cumulative heat release rate of 0.58 kJ, where as biodiesel Has rates of 0.56 kJ (B10), 0.54 kJ (B20), and .52 kJ (B30). It can be seen that biodiesel mixes release energy from the fuel more quickly than diesel fuel. This is because diesel combustion begins later than that of biodiesel mixes due to a longer ignition delay time, but it rapidly outpaces it, showing that diesel burns more quickly. During the diffusion phases, the cumulative heat release rate does not depart much from that of pure diesel.

5.1.5 Mean Gas Temperature

Diesel fuel has a maximum gas temperature of 900.21 ^{o}C, while biodiesel blends have maximum gas temperature of 891.21 ^{o}C (B10), 882.5 ^{o}C (B20), and 859.65 ^{o}C (B30). This shows a 1%, 2%, and 4.4% difference in values between B10, B20, and B30 biodiesel blends and diesel, respectively. The air's temperarure at the point of maximum compression is high enough, as can be seen, for the fuel droplets to evaporate and ignite as they enter the cylinder. In the case of diesel fuel, the gas temperature is higher during the combustion stage, resulting in increased pressure during the combustion phase. Fig. 5.6 depicts how the mean gas temperature varies for diesel and biodiesel mixes in relation to the crank angle.

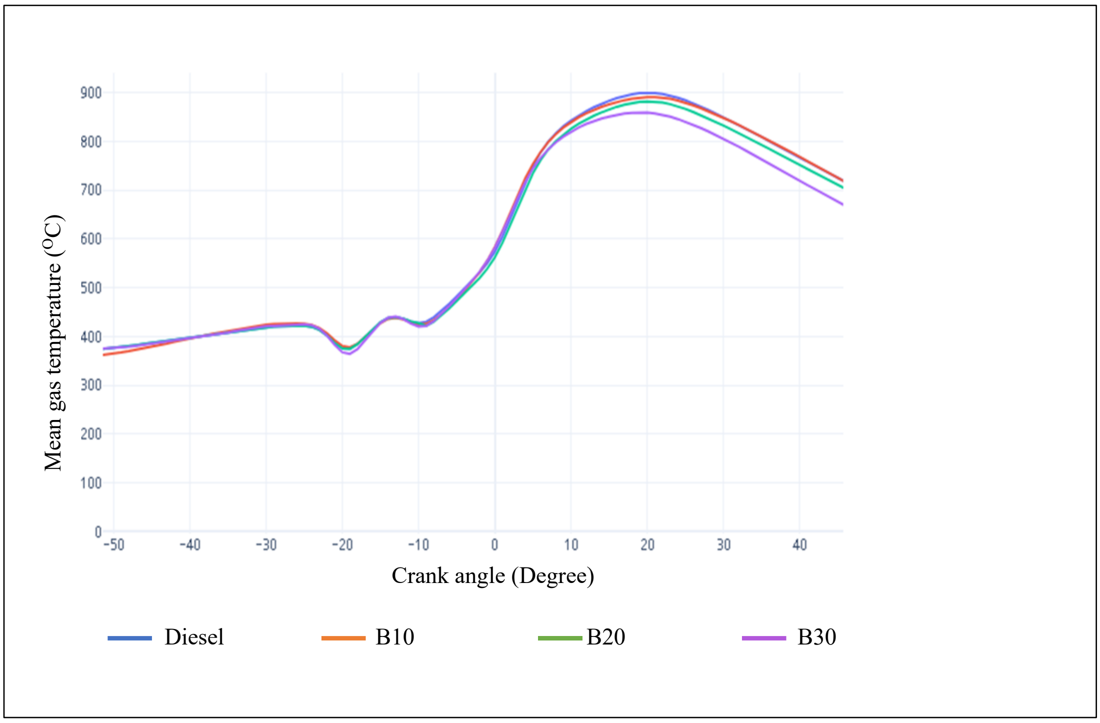


Fig. 5.6 Mean gas temperature vs. crank angle

5.2 Engine Performance

Any fuel's characteristics have a big impact on how well an engine performs. Due to its greater oxygen contents, higher heat of vapourization, higher density, higher viscosity, lower heating values, and higher cetane number, biodiesel has a significant impact on engine performance [5]. Because of the greater cetane number and shorter ignition delay, biodiesel has a higher peak in-cylinder pressure than diesel [162]. This is also attributed to the biodiesel's greater oxygen concentration, which led to better burning. Because of its higher density and lower energy content, biodiesel fuel is said to have a higher brake specific fuel consumption (BSFC) than diesel [110]. While the lower heating values and greater viscosities of biodiesel were to blame for the decreased Brake power (BP) of the fuel when compared to diesel [5]. This study evaluated the impact of methyl esters from Croton megalocarpus, coconut, and calophyllum inophyllum on engine performance as measured by torque, brake power (BP), and brake specific fuel consumption (BSFC) [163]. The outcomes of these parameters will be discussed in the section follows.

5.2.1 Engine Torque

Engine power is generated by the spinning of a shaft that applies the necessary amount of torque to a load at a specific RPM. Fig. 5.7 depicts the change in diesel torque for engines using B10 and B20 at different engine speeds, under full load [163]. Because power output rises with load, torque values also rise. For all load levels, diesel has higher torque values than biodiesel mixes. At a heavy load of 14.7 kg, the greatest torque produced by diesel fuel was 27.67 Nm, but the maximum torque produced by the biodiesel blends B10, B20, and B30 was 26.67, 26.1, and 25.47 Nm, respectively. The maximum torque values of the B10, B20, and B30 differ from each other by 3.6%, 5.8%, and 8%, respectively. The combination of biodiesel's increased viscosity and density and its lower calorific value may have reduced the torque values for the biodiesel blends.

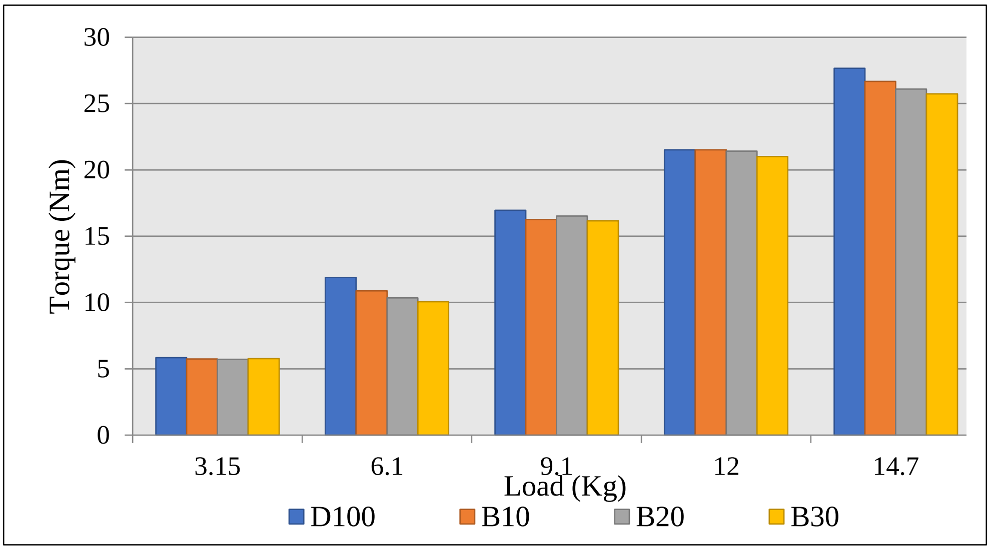


Fig. 5.7 Torque vs. Load

5.2.2 Brake Power

Brake power, which is always smaller than stated power, is the real power available at the crankshaft. Fig. 5.8 depicts the variance in diesel brake power (BP) for engines at various speeds under full load. Fig. 5.8 shows the fluctuations in brake power levels in proportions to engine loads. At all loading settings, the experimental brake power values while using biodiesel blends were lower than diesel values, and they got worse as the blending ratios increased. At 14 kg of load, the biodiesel blends B10, B20, and B30 had respective maximum brake power of 4.20 kW. Maximum brake power ratings of biodiesel blends B10, B20, and B30 differ from diesel by 0.95%, 1.4%, and 1.7%, respectively. Generally, biodiesel-diesel mixtures have less brake power than pure diesel. Additionally, the steady rise in brake power with engine speed is noticed in various research work. Their lower heating values and greater viscosities as compared to diesel are the reasons for this reduction.

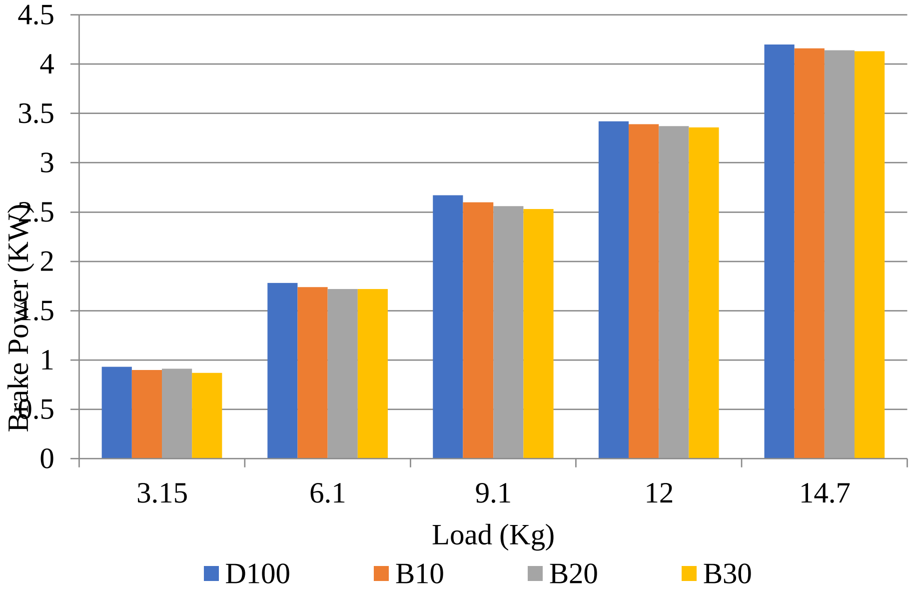


Fig. 5.8 Brake power vs. Load

5.2.3 Brake Thermal Efficiency

Brake thermal efficiency (BTE) is the ratio between the power output and the energy introduced through fuel injection, which is the product of the flow rate of injected fuel mass and the lower heating value. It is defined as the breaking power of a heat engine as a function of the thermal input from fuel. It serves as a gauge for assessing how well an engine transfers heat from a fuel to mechanical energy. Fig. 5.9 compares the brake thermal efficiency attained for pure diesel and biodiesel blends. It is obvious that diesel has a BTE that is somewhat higher than that of biodiesel blends. Additionally, it falls as the blending ratio rises. The maximum BTE for diesel fuel is 20.97%, while the corresponding figures for the biodiesel blends B10. B20, and B30 are 20.77%, 20.34%, and 19.99%, respectively. This is because, when compared to diesel fuel, biodiesel has a higher density, viscosity, and lower heating value. Higher viscosity causes less fuel atomization and vaporization, which lowers biodiesel BTE values. In comparison to diesel, the percentage differences for B10, B20, and B30 are 0.95%, 3%, and 4.76%, respectively. Additionally, it can be shown that BTE increases first as load increases, reaches a maximum value, and then begins to decrease as load grows further. The main factor is that as load grows, power output likewise rises until the maximum BTE is reached. As load rises higher, heat losses also rise, which lowers the value of BTE.

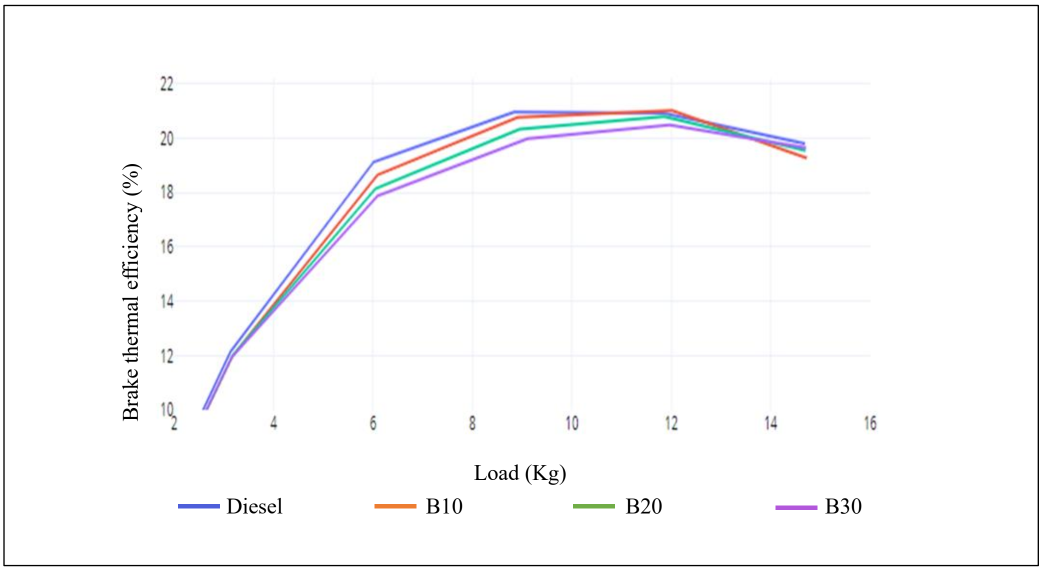


Fig. 5.9 Brake thermal efficiency vs. Load

5.2.5 Brake Specific Fuel Consumption

The link between the volumetric fuel injection system, fuel density, viscosity, and energy content has a major impact on the BSFC of diesel engines [164]. The variance in brake specific fuel consumption (BSFC) for diesel, B10, and B20 blends at various engine speeds and full load conditions is depicted in Fig. 4.11. When biodiesel blends are utilized, it can be seen that the BSFC values are greater [165]. Due to their greater density and lower energy content, biodiesel-diesel blends have a higher BSFC than pure biodiesel. The volumetric delivery of any gasoline to the engine is used. An increase in fuel density for a given fuel volume would indicate a higher mass flow rate to the cylinders, which would raise the BSFC to create the same amount of power [163]. The quantity of fuel used by a vehicle for each unit of output is known as specific fuel consumption. The SFC (kg/KWh) fluctuation of diesel and biodiesel blends with regard to load (kg) is shown in Fig. 5.10 for an engine running at 1500 rpm. Being an oxygenated fuel, biodiesel’s inclusion had varying impacts on the operation and combustion at various engine loads. Its inclusion was most successful when there was rich combustion n due to high engine loads. Low engine loads resulted in less gasoline being delivered to the engine and a further leaning of the total mixture. As a result, the generalized specific fuel consumption rises at low loads, falls at middle loads, and then rises once again at high loads.

At low engine loads, B10, B20, and B30 have maximum specific fuel consumption rates of 0.70, 0.72, 0.73, and 0.75 kg/kWh, respectively, with a percentage difference of 2.85%, 4.28%, and 7.14% when compared to diesel. Under all types of engine loads, the SFC values of the biodiesel blends are just a little bit greater than hose of diesel fuel. This is because biodiesel has a lower heating value than diesel fuel, which results in a higher fuel consumption rate and less power, requiring more of it to create the same amount of energy. Additionally, because biodiesel has a higher density than diesel fuel, the same volume of fuel consumed with biodiesel has a higher specific fuel consumption (SFC).

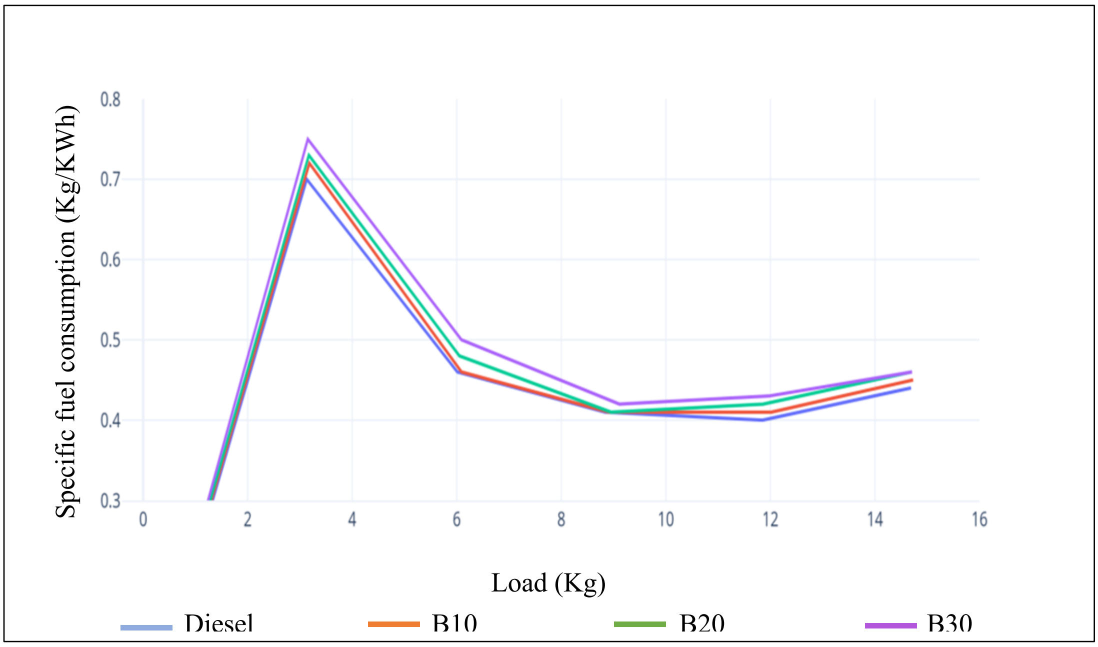


Fig. 5.10 Specific fuel consumption vs. Load

5.2.6 Exhaust Gas Temperature

The graph of exhaust gas temperature (EGT) versus crank angle in a Compression Ignition (CI) engine combustion cycle provides insights into the thermal behavior of the combustion process [166]. The crank angle represents the angular position of the engine's crankshaft, and it is used as a measure of time in the engine cycle. The graph of exhaust gas temperature vs. crank angle in a CI engine provides a dynamic view of the combustion process to analyze and optimize combustion conditions, enhance engine efficiency, and control emissions in compression ignition engines. The graph usually shows a rapid increase in exhaust gas temperature during the combustion phase. This temperature rise corresponds to the period when the fuel injected into the combustion chamber ignites and undergoes combustion. The peak of the EGT curve represents the highest temperature reached during this phase. Following combustion, there is an expansion phase where the high-pressure and high-temperature gases expand, driving the piston down. This is followed by the exhaust phase when the exhaust valve opens, and the burnt gases are expelled from the cylinder. During these phases, the EGT gradually decreases. The shape of the EGT curve can provide information about the temperature distribution within the combustion chamber during the engine cycle. It helps in understanding how well the combustion process is occurring and whether there are any irregularities. The rate of change of exhaust gas temperature with respect to crank angle can give insights into the heat release rate during combustion. This information is valuable for optimizing engine performance and controlling emissions. The EGT vs. crank angle data can be used to optimize combustion parameters such as injection timing, air-fuel ratio, and compression ratio. Controlling these parameters effectively can lead to improved efficiency, reduced emissions, and enhanced engine performance. The EGT curve is closely related to the formation of pollutants, such as nitrogen oxides (NOx) and particulate matter. Monitoring EGT helps in understanding the combustion conditions that influence emission levels.

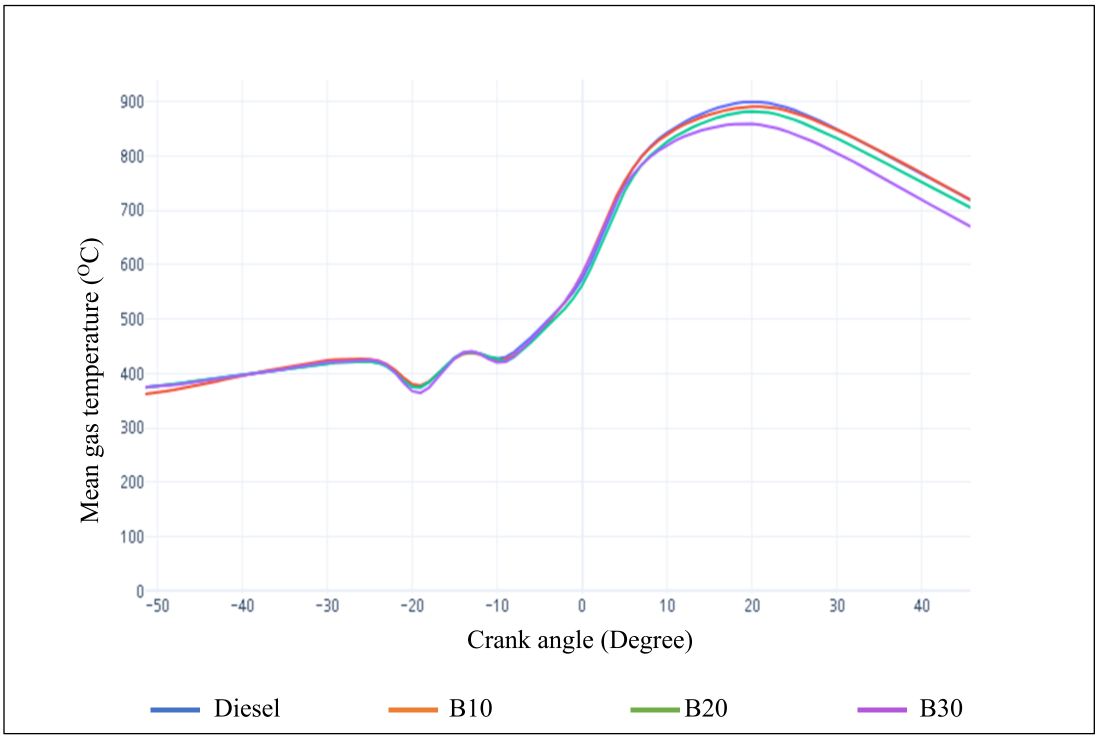


Fig. 5.11 Mean gas temperature vs. crank angle

5.3 Energy Analysis for Varying Compression Ratio

Energy analysis of any thermodynamic system is done by evaluating its energy flow. For IC engines, this analysis includes evaluating BTE, BSFC, and losses through various modes. Further, this analysis works as an impetus for exergetic analysis. As the main cause of inefficiency is heat losses, finding multiple ways of it and allocating contributions of all modes help much in improvising the system. The reduction in the proportion of energy losses carried away by various modes at designated loads suggests the better conversion of energy to useful work and hence an improved thermodynamic system, specifically a better bio-fueled CI engine in the present case.

5.3.1 Energy/Fuel Input

The effects of compression ratio on energy distributions through control volume for B20 are shown in Fig. 5.12. The shaft energy distributions increase for change in CR from 15:1 to 17.5:1 and decrease after that. Power output (Q_s) showed an increasing trend for compression ratio in the range of 15 to 17.5 and decreased thereafter. This trend may be attributed to increased stroke volume [33]. The energy carried by exhaust gases and the cooling water follows the same suit and decreases till the compression ratio of 17 and then increases, but both change their stance after CR of 17.5. The energy carried away by the exhaust gases is minimal at CR of 17 and maximum at CR of 18, showing better efficiency between CR of 17 and 18. The un-counted losses increase up to CR of 17 and decrease after that. A compression ratio of 17.5 was found to be optimum because of faster distribution of fuel with the rise in

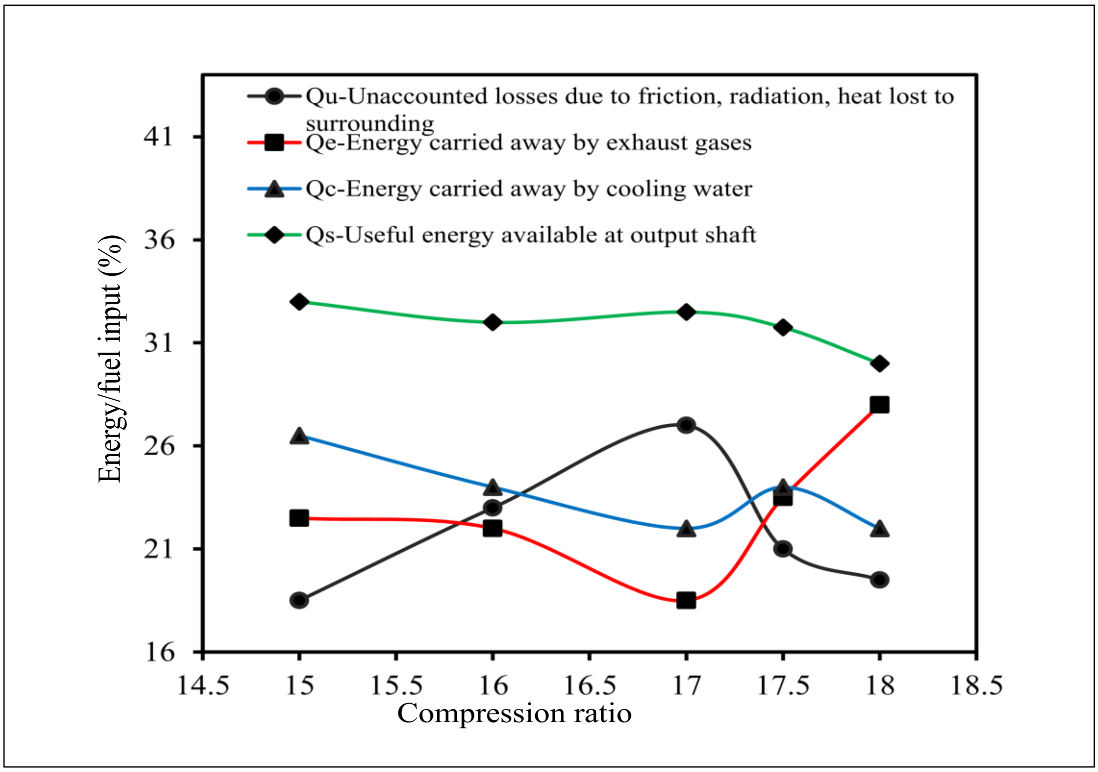


Fig. 5.12 Energy flow through different modes at a different compression ratio for B20

5.3.2 Brake Thermal Efficiency

Brake power is the actual work output measured at the dynamometer. BTE is the brake power of an IC engine as a function of thermal input from fuel [167]. BTE best explains the conversion of fuel's chemical energy into useful work since the calculation of brake thermal efficiency includes brake power, heating value, and mass of the fuel [168]. For varying compression ratios, BTE was obtained for different fuel samples of B20 and pure diesel, as shown in Fig. 5.13(a). It was observed that when compared with diesel fuel, the use of oxygenated fuels increases thermal efficiency [91]. From CR of 15:1 to 17.5:1, the difference between the BTE of B20 and diesel is found to be decreasing and meets at the CR of 18, as shown in Fig. 3. This better performance may be attributed to better cone spray formation of B20 and oxygen content present in it [169]. It may be due to its burning velocity and shorter ignition delay of biodiesel to burn the fuel completely at a higher compression ratio [170]. As it can be observed that for B20, the maximum BTE is observed for CR of 17.5:1. The results show that the rise in CR raises BTE and reduces the BSEC of B20 with diesel.

5.3.3 Brake Specific Energy Consumption

It has been observed that the BSEC of B20 is lower than diesel because of its homogeneous mixture of fuel with air [171]. Though there was a slight rise in BSEC on increasing CR from 15:1 to 17:1, it was the least for CR of 17.5, as shown in Fig. 5.13 (b). For all of CR mentioned above, the mass of fuel ($\dot{m}_f$) consumption of B20, as shown in Fig. 3, is found to be 0.77, 0.78, 0.8, 0.75, and 0.76 kgh^{-1}, respectively, which is lower than diesel for the corresponding CR.

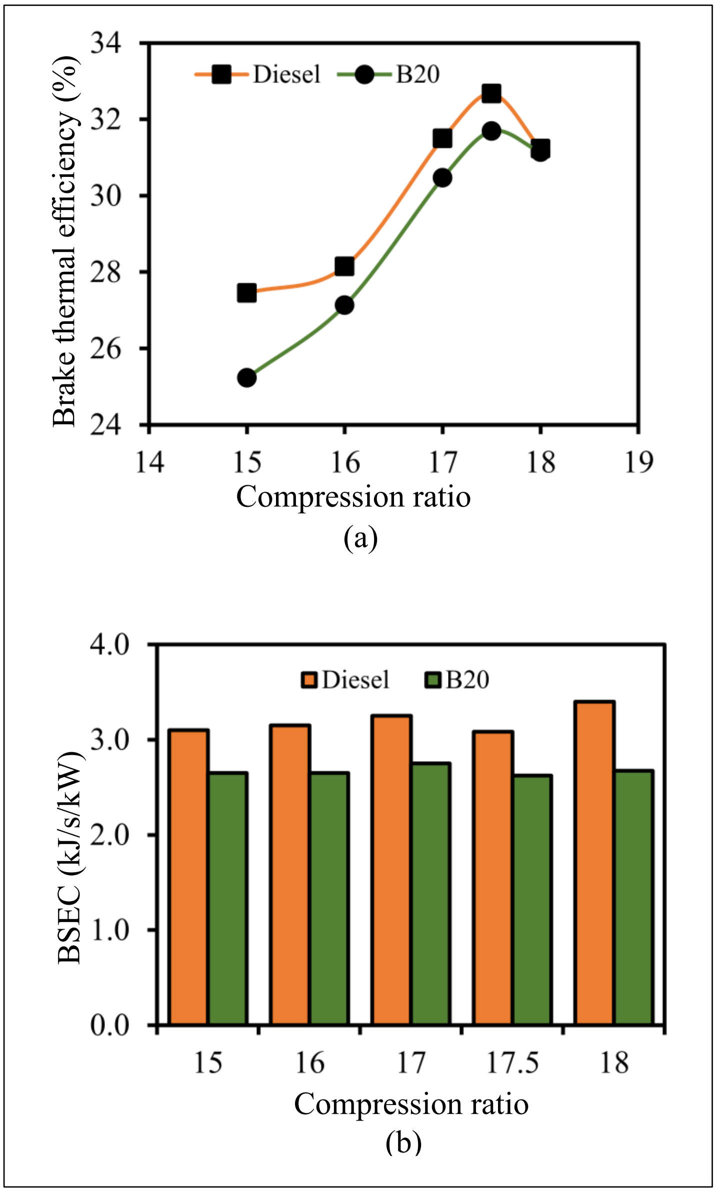


Fig. 5.13 (a) Brake thermal efficiency vs. compression ratio, (b) Brake-specific energy consumption vs. compression ratio for diesel and B20

5.4 Exergy Analysis for Varying Compression Ratio

From the thermodynamics perspective, exergy is the highest amount of work obtained from the balanced system. Few studies show that the chemical exergy of fuel is an important factor to be considered along with the mass and heating value of the fuel [169]. The exergetic efficiency can best describe engine operation as the operations are analyzed from the perspective of the first as well as the second laws of thermodynamics which includes exergy losses and exergy destructions. These losses and destructions are all because of flow losses and mixing, turbulence, combustion, etc.

Before analyzing the exergy balances through different modes, it is useful to examine the entropy. Entropy generation leads to inefficiencies in the system due to irreversibility. As depicted in Fig. 5.14, entropy generation follows a reverse trend than exergy efficiency. The exergy efficiency of diesel has shown a sudden jump at CR of 17.5 and flat after a further increment of CR. Though exergy efficiency is higher for diesel than B20, both follow the same trend and minimum value at CR 17 and increase afterward for B20. The Dome shape of the entropy generation curve for B20 is explained by its lower volatility, and diesel is due to an increase in stroke length [172]. For B20, exergy efficiency is maximum at CR of 18, and also entropy generation is least at the same CR.

5.4.1 Availability

In the context of thermodynamics, availability (also known as exergy) is a measure of the maximum useful work that can be obtained from a system as it comes into equilibrium with its surroundings [173]. Availability is a more comprehensive and insightful measure compared to energy or entropy alone. For a combustion process, such as in a Compression Ignition (CI) engine, availability considerations help in assessing the quality of the energy and how much of it can be converted into useful work. The availability (A) of a system is defined as the difference between the total energy of the system (H) and the product of the absolute temperature (T) and the entropy (S)·

$$A = H - T \cdot S$$

The availability analysis takes into account the chemical reactions occurring during combustion and their irreversibilities. This analysis helps to identify areas where improvements can be made to enhance the efficiency of the engine. Availability analysis provides a more detailed perspective on the quality of energy and the potential for converting it into useful work for engine combustion. Availability analysis is particularly useful for assessing the performance of engines and optimizing their design and operation. It can also be applied to evaluate the impact of irreversibilities and losses in the combustion process and identify opportunities for improving overall efficiency. For a combustion process, the availability of the fuel before combustion is associated with its chemical energy, and the availability after combustion is related to the thermal energy released. The goal is to maximize the availability of the useful work that can be obtained from the combustion process.

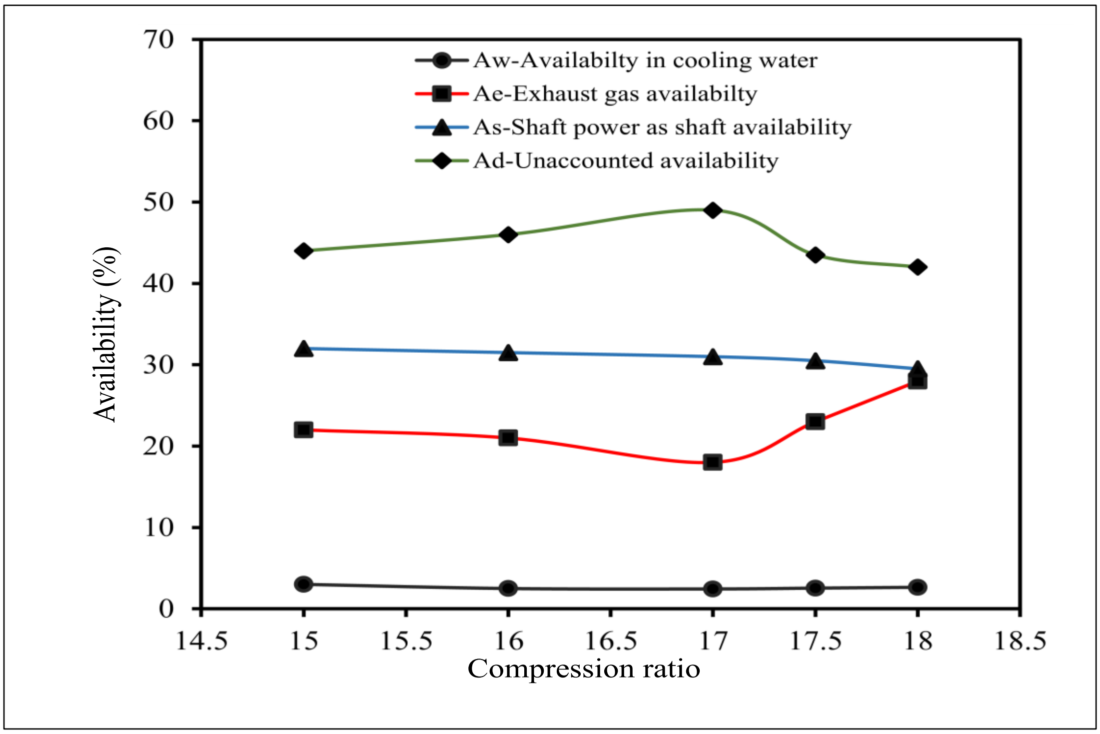


Fig. 5.14 Availability through various modes vs compression ratio

5.4.2 Exergy Efficiency

Exergy efficiency, also known as second-law efficiency or availability efficiency, is a measure of how well a system can convert the available energy (exergy) into useful work. In the context of a Compression Ignition (CI) engine combustion, exergy efficiency is a way to evaluate the efficiency of the engine from a thermodynamic perspective, considering the irreversibility and losses in the combustion process. The exergy efficiency provides a more detailed assessment of the quality of the energy conversion in a system compared to thermal efficiency alone. It takes into account not only the energy content of the fuel but also the thermodynamic quality of that energy. In practical terms, achieving high exergy efficiency in a CI engine involves minimizing irreversibility, optimizing combustion conditions, and considering factors such as compression ratio and heat transfer losses. The exergy efficiency (η_{ex}) is defined as the ratio of the useful work obtained from the system to the exergy input (or availability input) of the fuel. Mathematically, it can be expressed as:

$$\eta_{ex} = \frac{W_{out}}{Ex_{in}}$$

where, W_{out} is the useful work output from the engine and Ex_{in} is the exergy input (or availability input) of the fuel. The exergy input (Ex_{in}) of the fuel can be calculated using the following relationship:

$$Ex_{in} = mf \cdot (H_{in} - H_0)$$

Where, m_f is the mass flow rate of the fuel, H_{in} is the specific enthalpy of the fuel at the combustion conditions, H_0 is the specific enthalpy of the fuel at a reference state.

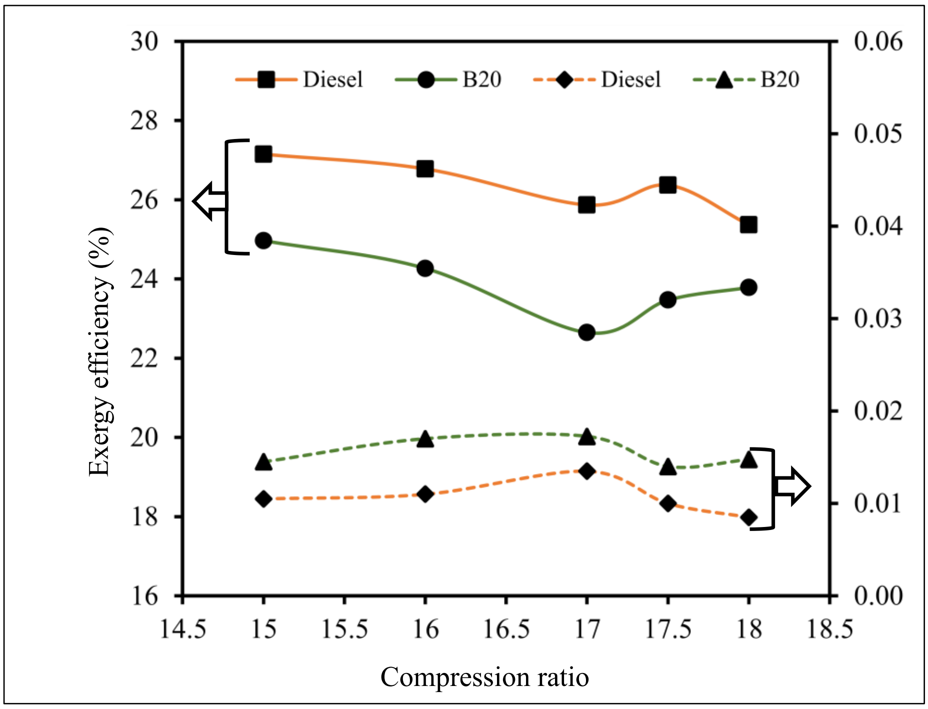


Fig. 5.15 Exergy efficiency and Entropy generation vs. compression ratio

5.5 Energy Analysis for Varying Fuel Injection Pressure

This section elaborates on the effect of fuel injection pressure, which was taken at 170, 180, 190, 200, 210, and 220 bar for performing exergy and energy analysis of B20 and diesel on the test engine. Fuel injection pressure influences air-fuel mixture formation and atomization before combustion.

Combustion process in the engine ensures that a fraction of the fuel exergy is converted to brake power, and the remaining is lost in different proportions through various modes. These losses are accounted for to find the engine operating condition at which the exhaust exergy losses are minimal. Fig. 7 depicts heat losses through various sources, e.g., cooling water, exhaust gases, and unaccounted losses. The combustion in the cylinder takes place more efficiently in fuel with a high cetane number [174][175]. As it is found out that cetane no. of B20 is higher, combustion starts early; hence the ignition delay is shorter. Another good reason for the better combustion of

B20 is its higher oxygen content [176]. These are two probable reasons for the higher exhaust exergy rate of biodiesel fuel (B20) than diesel fuel. It could be inferred from Fig. 7 that the unaccounted losses are the maximum of all losses, which includes losses accounting for friction, radiation, the heat lost to the surrounding, etc. Another noticeable conclusion made from this graph is that the share of unaccounted losses in the case of B20 is far less than pure diesel, almost 20% less.

5.5.1 Net-Work Rate

In a CI engine, the combustion of fuel occurs due to the high temperature resulting from the compression of air in the cylinder. The expansion of the burning gases forces the piston down, and this motion is converted into useful work. It's important to note that the net work rate is different from the indicated work rate, which includes all the work done on the piston during the combustion process. The net work rate takes into account factors such as friction and other losses that reduce the efficiency of the engine. The net work rate of a Compression Ignition (CI) engine refers to the rate at which useful work is produced by the engine. In the context of internal combustion engines, net work rate is often expressed in terms of power, which is the rate of doing work. The net work rate can be calculated as;

$$Net\ work\ rate = \frac{Net\ Work\ Output}{Time}$$

The net work output is the work done by the engine on the piston, which is typically measured in units of energy such as joules or kilojoules.

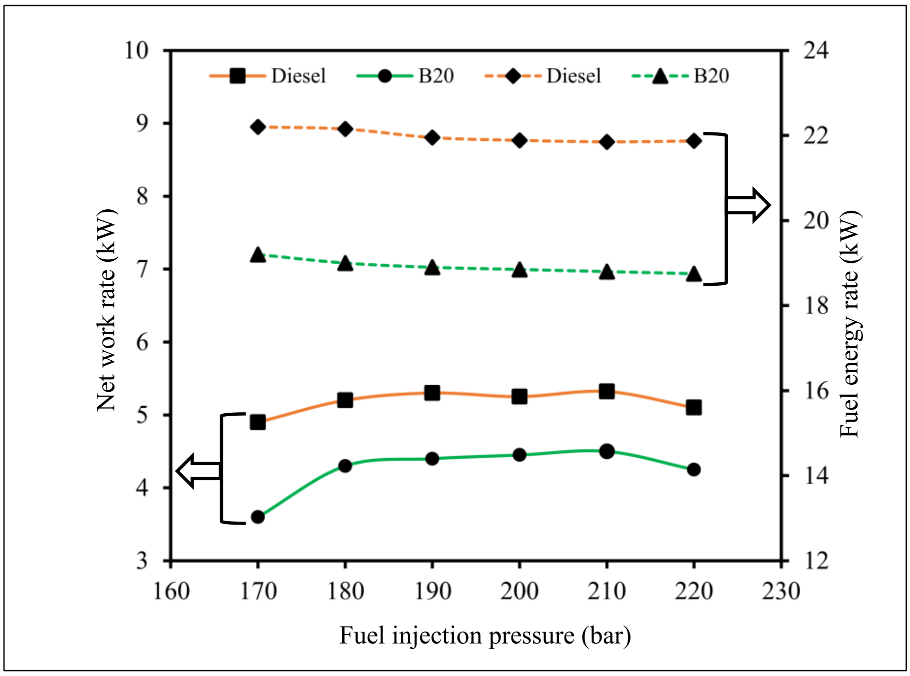


Fig. 5.16 Net work rate and Fuel energy rate vs fuel injection pressure

5.5.2 Fuel Energy Rate

In the context of internal combustion engines, the fuel energy rate is often related to the brake power output of the engine. Brake power is the useful mechanical power delivered by the engine's crankshaft to an external load. The fuel energy rate is a measure of the rate at which energy is released from the combustion of fuel and is a fundamental parameter for evaluating the performance and efficiency of combustion systems. It is a measure of the amount of energy released per unit of time during the combustion process. It is an important parameter in assessing the performance of combustion systems, such as internal combustion engines. It provides information about the amount of energy available from the fuel and is crucial for determining the power output of the engine. The fuel energy rate is typically expressed in terms of power and is commonly measured in units such as watts (W), kilowatts (kW), or megawatts (MW). It has been observed that fuel energy rates of B20 are lower than pure diesel.

This may be due to the lower heating value of B20. Fig. 5.16 further strengthens this finding for all injection pressure. An important point to mention here is that the maximum work rate was obtained at the injection pressure of 190 bar for diesel and 210 bar for B20. This variation in pressure may be due to the improvement of atomization and mixing of fuel and air at higher injection pressure despite higher kinematic viscosity and density values [177].

The formula for calculating the fuel energy rate is:

$$\text{Fuel Energy Rate} = \text{Fuel Mass Flow Rate} \times \text{Heating Value of Fuel}$$

Where, Fuel Mass Flow Rate is the rate at which fuel is consumed, typically measured in units like kilograms per second (kg/s). Heating Value of Fuel is the amount of energy released per unit mass of the fuel during combustion. It is usually expressed in energy units per unit mass, such as joules per kilogram (J/kg).

5.5.3 Heat Loss Rate

The heat loss rate in the context of a Compression Ignition (CI) engine refers to the rate at which heat is lost from the combustion chamber to the engine components and surroundings during the combustion process. It is a critical parameter in the study of CI engine combustion because it affects the overall efficiency, performance, and emissions of the engine. An understanding of temperature patterns helps in designing components that can withstand high temperatures without excessive wear or damage. Knowledge of heat losses is essential for optimizing engine design parameters, such as cylinder shape, material selection, and cooling systems. This optimization contributes to better performance and durability [178]. The total heat release during combustion in a CI engine consists of useful work output and heat losses. Useful

Work Output (Brake Power) is the power delivered by the engine's crankshaft to perform useful work, such as moving a vehicle or generating electricity. Heat Losses include various forms of heat losses, such as convective heat transfer to the cylinder walls, conductive heat transfer through the engine components, radiation losses, and heat carried away by the exhaust gases.

$$Q_{loss} = Q_{total} - \text{Brake Power}$$

Where, Q_{total} is the total heat released during combustion and brake Power is the useful mechanical power delivered by the engine. High heat losses result in a lower thermal efficiency because a significant portion of the energy released during combustion is not converted into useful work. Minimizing heat losses is essential for improving overall engine efficiency. Heat losses are related to the temperature distribution within the engine.

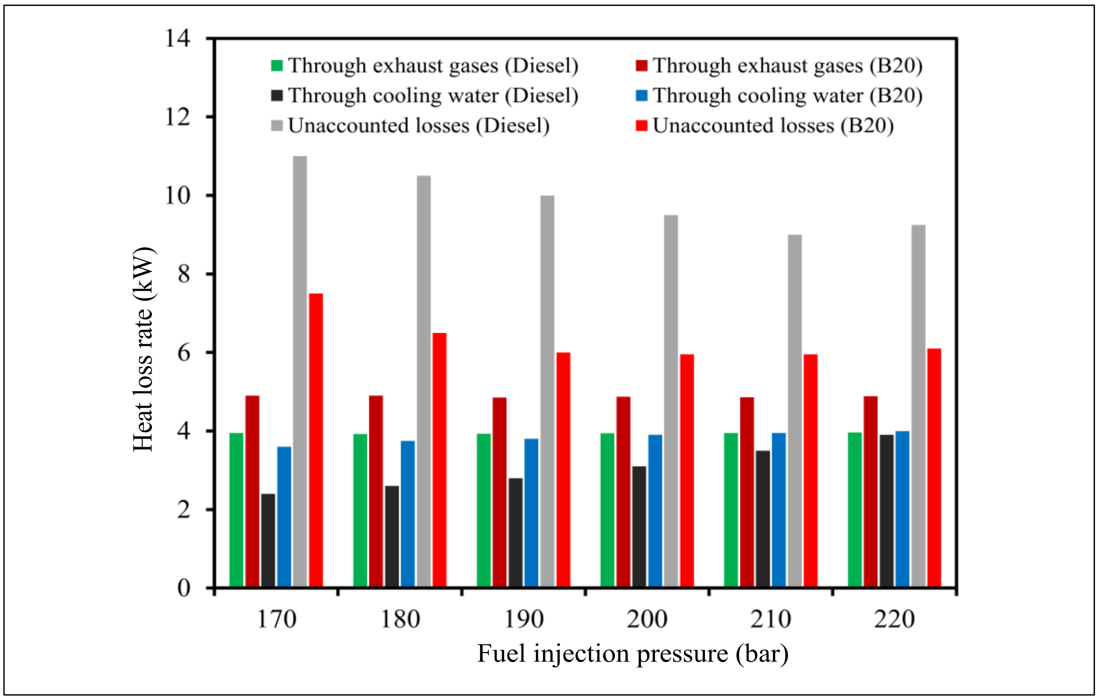


Fig. 5.17 Heat loss rate through various sources vs. fuel injection pressure

5.6 Exergy Analysis for Varying Fuel Injection Pressure

The energy analysis alone is insufficient to find the optimum fuel injection pressure for biodiesel blends (B20 in this case). Therefore, it's essential to perform exergy analysis and energy analysis to find the optimum operating parameters for the use of biodiesel in the CI engine. As shown in Fig. 5.18, exergy analysis was done with biodiesel (B20) and compared with pure diesel for fuel injection pressures of 170, 180, 190, 200, 210, and 220 bar.

5.6.1 Entropy Generation and Exergy Destruction

In general, exergy destruction is proportional to the process's entropy generation, and both are used interchangeably to understand the energy utilization quality for analyzing and optimizing thermal systems. Entropy generation only depends upon the state of the system, while exergy depends upon the state of the system and the environment. The exergy efficiency for diesel was found to be maximum at the fuel injection pressure of 190 bar, and for B20, it was at 210 bar. Better fuel atomization at higher injection pressure could be the probable reason for lower entropy generation for B20. The exergy destruction in percentage and entropy generation in kW/K is shown in Fig. 8. The entropy generation values of biodiesel (B20) are lower than those of diesel fuel. It is a well-established fact that exergy efficiency has an opposite trend with exergy destruction so the exergy efficiency trend can be estimated. As found experimentally, the entropy generation of pure diesel and biodiesel (B20) were 0.054 and 0.044 kW/K, respectively, when averaged for various injection pressure. A similar variation of entropy generation rates and maximum value of exergy destruction of the engine using diesel fuel at different ambient temperatures was reported in the experimental study by Sanli et al. [86], [179].

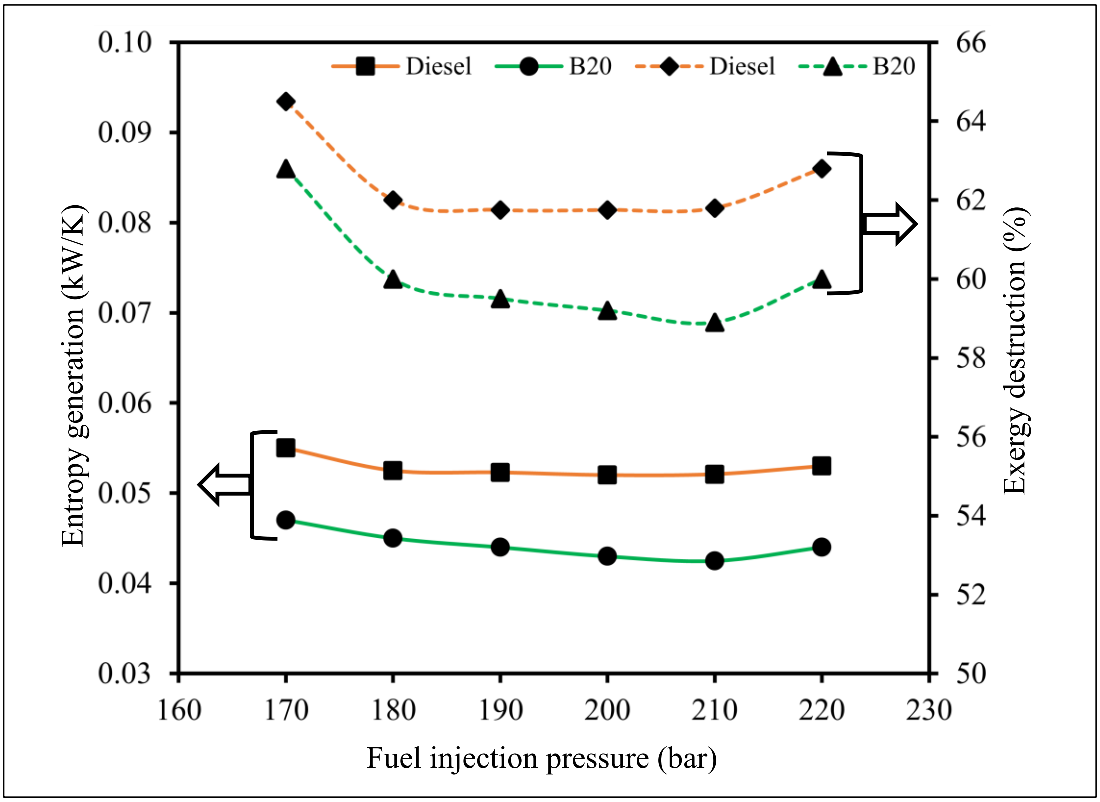


Fig. 5.18 Entropy generation and Exergy destruction rate vs fuel injection pressure

CHAPTER 6

CONCLUSIONS AND SCOPE

This chapter comprises of conclusions inferred from the experimental work and detailed analysis of performance, combustion, and energetic-exergetic study of biodiesel fuelled engines and few suggestions for the potential future work in this area. These results verify that tallow biodiesel could be used without any major engine modifications as an alternative and environmentally friendly fuel.

6.1 Conclusions

The available feedstocks for biofuel production have been categorized generation-wise as well as according to their origin. There are various sources of biofuel identified by scientists and researchers so far, which include edible oil, non-edible oil, animal fats, microbial feedstocks, waste cooking oil, etc. making biodiesel viable for use and economical for production. This work emphasized various selection criteria to choose better alternatives out of the available biofuel resources. Free fatty acid in biofuel mainly decides the quality of biofuel and identifies the most appropriate and cost-effective feedstocks for biodiesel selection for greater use. Waste cooking oil, because of its easy and wide availability, and Tallow oil, because of its economic viability and being environmentally friendly fuel; are two important biodiesel feedstocks to be considered for mass production and future use as an alternative to fossil fuels.

In the study of combustion and performance characteristics following major conclusions can be drawn:

- The combustion starts earlier for biodiesel blends than for diesel. In-cylinder pressure calculated by experiments for diesel was greater than biodiesel blends by 0.6 – 4.6 %.
- The mean gas temperature, heat release rate, brake power, and output torque were higher for diesel fuel with a maximum difference of 4.4%, 15.06%, 1.7%, and 8% respectively as compared to biodiesel blends, and these values decreased with an increase in blending ratio.
- Specific fuel consumption for Biodiesel blends was higher than diesel fuel due to the lower heating value of biodiesel by 2.85, 4.28, and 7.14% for B10, B20, and B30 respectively.
- BTE for biodiesel blends was about 5 % lower for biodiesel blends as compared to conventional Diesel fuel

The thermodynamic analysis at varying compression ratio and injection pressure on a compression ignition engine fuelled with diesel and B20 (80% diesel blended with 20% tallow biodiesel) is inquisitive and compared to pure diesel. To use a biodiesel blend economically and with propitious engine efficiency, operating points for B20 blend have been found. The important inferences that have been made are listed as:

- B20 is a better alternative to pure diesel without compromising performance and efficiency.
- Tallow biodiesel with the B20 sample gives the best results at a compression ratio of 17.5 and injection pressure of 210 bar.

- Maximum energy and exergy efficiencies for the B20 sample are of the order of 28.94 and 30.48%, respectively
- Unaccounted losses (due to friction, radiation, and heat loss to surroundings) contribute maximum to exergy destructions compared to other losses, which can be tapped for other use or minimized in future work to enhance efficiency.

As this work was carried out to suggest the operating points for having comparable engine performance and adopt an appropriate strategy, it may be deliberated as to use 20% biodiesel blended with pure diesel for economical use widely, as this was used for research purposes only till date except for few instances.

6.2 Challenges and future directions

The exergy-based approach is used as an effective tool to analyze energy transformations. The productivity, efficiency, and sustainability of energy-intensive systems are categorically explained by thermodynamic, economic, economic, and environmental analysis. The exergy concept uniquely evaluates the energy flows and the sustainability issues involved in energy in transit. Major challenges in exergy calculation is its dependence on reference state's choice and difficulties in assessing it. Exergy evaluation itself provide limited knowledge of efficacy of any system. The research works published about exergy analysis of biofuel systems cannot provide useful information about economic and environmental aspects. The application of exergy concept integrated with economic accounting and environmental assessment results into quality conclusions. Mae and Van Passel [180] evaluated the sustainability aspects of bioenergy and biomaterials production processes using exergetic indices and explained the related pros and cons. The future work should be oriented towards integrating exergy concept with available economic accounting and environmental impact assessment dealing with real-world constraints. The resultant conclusions' quality can be enhanced by exergy economic and exergy environmental approaches consisting of actual economic and environmental constraints as complementary tools. Aghbashlo and Rosen [181] proposed the exergy economic environmental method to understand the biofuel production system from the thermodynamic, economic and environmental viewpoints. Sciubba [182] included all physical and nonphysical inputs to energy systems on the basis of exergy only using the concept of exergy accounting method [183].

Exergy efficiency has been categorized as universal and functional exergy efficiency. Universal exergy efficiency determines the level of exergy loss (due to irreversibility and heat loss) but cannot measure the exergetic usefulness of any system. This issue is addressed by functional exergy efficiency which measures the level of the effectiveness and productiveness of a particular system. Future research work on biofuel systems should be focused on finding functional exergy efficiency. The exergy has two forms in the biofuel production systems, chemical exergy, and physical exergy. The chemical exergy contributes more to total exergy of the streams involved in biofuel production system than physical exergy. Accurately computing the chemical exergy of organic compounds is tedious work and needs to be further assessed by working on different approaches and formulas.

The exergy analysis provides information regarding the thermodynamic interactions among the components of systems but cannot quantify the avoidable portion of the thermodynamic inefficiencies. Tsatsaronis and Morosuk [184] used advanced exergy-based methods and fractionated the exergy destruction along with its associated costs and environmental consequences into avoidable endogenous, avoidable exogenous, unavoidable endogenous, and unavoidable exogenous parts. This approach significantly and substantially improved the quality and accuracy of the conclusions derived from exergy, exergy economic, and exergy environmental.

There are various exergetic indicators used in analyzing biofuel systems but, none of them are universally agreed upon. The absence of standardization in exergetic indicators make it harder to analyze exergetic data from various studies. Sometimes, the interpretations of results are misunderstood and found to be contradictory due to different terminologies. For example, Arredondo et al. [185] introduced a new exergetic parameter, namely "Renewability Performance Indicator" as an exergy environmental indicator. Velasquez et al. [186] contradicted this indicator and concluded that it's an exergetic index. Meyer at al. [187] stresses that the exergy environmental approach is a combination of life cycle assessment and exergy concept. Therefore, the future research on biofuel systems should focus on standardized terminologies and their notations.

Recently, a new methodology called "exergetic life cycle assessment" is adopted for biofuel systems by considering all of the energy inputs during production process. In addition to that, the majority of these studies are focused on biofuel production from bioethanol. The exergetic life cycle assessment should be applied to biorefinery with biofuels and bioproducts. The approach in system modeling, boundaries considered, processes carried out, exergetic formulations, assumptions made and simulations procedure were diverse in reported studies. This results in ambiguity in reported values for similar biofuel systems and it becomes difficult to find their applicability in real world without considering their experimental uncertainties and repeatability errors. Further, performance analysis of biofuel plants along with thermodynamic modelling of the processes are required to be done in future studies. The variations in feedstock compositions at different conditions along with the chemical formulas should be incorporated in these studies.

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LIST OF PUBLICATIONS

<u>Internation Journal:</u>

List of Publications Based on the Research (present) work

1. Kumar, Saket, and Raghvendra Gautam. "Energy and exergy assessment of diesel-tallow biodiesel blend in compression ignition engine for engine design variables." *Sustainable Energy Technologies and Assessments* 57 (2023): 103305.
2. Kumar, Saket, and Raghvendra Gautam. "Prospects of Factor Affecting Biodiesel Selection Strategies Based on Various Aspects: An Indian Perspective." *Journal of Engineering Research (2307-1877)* (2022).
3. Gautam, Raghvendra, and Saket Kumar. "Performance and combustion analysis of diesel and tallow biodiesel in CI engine." *Energy reports* 6 (2020): 2785-2793.
4. Kumar, Saket, Raghvendra Gautam, and Manish Kumar. "Multi-aspect assessment and multi-objective optimization of preheated tallow biodiesel-diesel blend as alternate fuel in CI engine", Environmental Progress & Sustainable Energy. Manuscript ID: EP-24-015. (Revision submitted-R1 Submitted).
5. "A Comprehensive Analysis on Cost, Combustion, Performance, and Emissions for Diesel Engine Fueled with Preheated Esters of Wate Cooking Oil", Journal-*Clean Technologies and Environmental Policy*. (Submitted)
6. "CFD simulation of Engine Combustion for Biodiesel Surrogate with A Reduced Reaction Mechanism Sprayed in CI Engine", Journal- *Process Safety and Environmental Protection*. (Submitted)

International Conferences:

1. Research article presented entitled "One dimensional modelling and simulation of injection parameters on the combustion, knocking, and emissions behaviour for biofuel" for conference "ICARI-2022, Delhi" on 6-7th March 2022.
2. Research article presented with Paper ID: ICERTSD 2023-132 in ICERTSD 2023 on 27th – 28th April, 2023 on the topic "Assessing Exergetic and Sustainability Parameters of Tallow Biodiesel-fueled Diesel Engine."
3. "The Impact of Metallic Nanoparticles in Biodiesel Fuel Blends: A Comprehensive Review Physiochemical Properties and Emission Characteristics" in 2nd National Conference on New Horizons in Science, Engineering, Management and Humanities at IIMT, Greater Noida.

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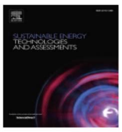

Energy and exergy assessment of diesel-tallow biodiesel blend in compression ignition engine for engine design variables

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Performance and combustion analysis of diesel and tallow biodiesel in CI engine

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Prospects of Factor Affecting Biodiesel Selection Strategies Based on Various Aspects: An Indian Perspective

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CERTIFICATE OF PARTICIPATION

This is to certify that Dr./~~Mr./Ms~~. **Saket Kumar** presented/attended/~~volunteered~~ paper entitled "**One-Dimensional Modeling and Simulation of Injection Parameters on the Combustion, Knocking, and Emissions Behavior for Biofuel**" for "**International Conference of Advance Research and Innovation (ICARI-2022)**" organized by International Journal of Advance Research and Innovation (www.ijari.org), held online on 5th March 2022.

We express our heartfelt gratitude to him/her for sparing valuable time and enabling us in successfully organizing ICARI-2022.

Ramakant Rana
Co-Convener

Dr. Bhupendra Singh Chauhan
Conference Chair

2nd International Conference on Energy Resources and Technologies for Sustainable Developement ICERTSD-2023

Certificate of Participation

This is to certify that **Prof./Dr./Mr./Ms.** Saket Kumar has participated in the **2nd International Conference on Energy Resouces and Technologies for Sustainable Development (ICERTSD-2023)**, organized by the **Department of Mechanical Engineering, Indian Institute of Engineering Science and Technology, Shibpur, India,** during 27th and 28th April 2023.

Paper Presented by the participant: Assessing Exergetic and Sustainability Parameters of Tallow Biodiesel-fueled Diesel Engine

Mode of Participation/Presentation: Virtual (Online)

DR. PRADIP MONDAL
Jt. Coordinator, ICERTSD 2023

DR. SUDIP GHOSH
Chairman, ICERTSD 2023

DR. MUKESH KUMAR
Jt. Coordinator, ICERTSD 2023

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BRIEF PROFILE

Saket Kumar is currently working as an Assistant Professor in Dronacharya Group of Institutions, Greater Noida, India. After completing his higher secondary education from Jamshedpur Cooperative College, Jamshedpur; he did his B.Tech in the Department of Mechanical Engineering from Cochin University of Science And Technology, Kerala in the year 2012; M.Tech in Thermal Engineering from Delhi Technological University, Delhi, India in 2015. He joined Department of Mechanical Engineering, Delhi Technological University as Ph.D. Scholar in January 2019 and submitted his doctoral thesis on 29th December, 2023.

Mr. Saket did CFD analysis of hydrodynamic depressor using ANSYS as his B. Tech project and simulation of bio-fueled compression ignition engine as his M. Tech project. His Ph.D. work is focused on thermodynamic analysis of biofueled compression ignition engine. His research aims to use the advanced technologies to cater the needs of mass and to suggest solutions to global problems.

He has published three SCI/SCIE and two Scopus-indexed scientific research papers. Besides this, three other research papers are under review in SCI-indexed journal and one book chapter is under publication stage. In recognition of his research contribution, he has been named in DTU Research Excellence Award-2024 for executing commendable research work in the year 2023.

In the opinion of this author, the relevance of exergy to its many applications (ecology, systems theory, lifecycle assessments, power production etc) depends on how well exergy proponents can reassess the theory. Despite all the problems related to resource consumption methodologies and exergy, there is a need to understand energy flows in the world. At this point the door is still open for some fresh new ideas; both to reinterpret what is already known, and to provide meaning for what isn't with collaborative research.