EXPERIMENTAL INVESTIGATION OF LOW-CARBON AND CARBON-FREE FUELS IN A SPARK IGNITION ENGINE

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

DINESH M H

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE -575025

MARCH, 2023

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DECLARATION

I hereby *declare* that the Research Thesis entitled "**Experimental investigation of low-carbon and carbon-free fuels in a spark ignition engine**" which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in "Department of Mechanical Engineering" is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Date:28/03/2023

CERTIFICATE

This is to *certify* that the Research Thesis entitled "**Experimental investigation of low-carbon and carbon-free fuels in a spark ignition engine**" submitted by **Dinesh M H, (Register Number: 197092ME020)** as the record of the research work carried out by him, *is accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy.

Dr. Kumar G. N.

(Research Guide)

Date: 30/03/2023

Chairman – DRPC

Date: 30.3.2023

Dedicated to my

Beloved Parents

&

Teachers

Whose Love and Support
Sustained Me Throughout

ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude and respect to my research supervisor and the backbone of my entire research, **Dr. Kumar G. N.**, Associate Professor, Department of Mechanical Engineering, NITK Surathkal, for his uninterrupted support and guidance throughout my research. It is my privilege to have a Guru like him who gave me the freedom to work with routine check and proper instructions to shape the project. I thank him for his motivations and for prompting me at the right time to improve my research awareness, even during the difficult times of Covid 19. I am grateful to him for allowing me to overcome several challenges and difficulties that arose during the research process. I would also sincerely thank **Prof. Prasad Krishna** the Director, NITK Surathkal, **Dr. Udaykumar R. Yaragatti**, and **Dr. Karanam Uma Maheshwar Rao**, former Directors, NITK Surathkal, for providing adequate facilities to carry out my doctoral research.

I sincerely pay my gratitude to the Research Progress Assessment Committee members, including **Dr. Veershetty Gumtapure** (Associate Professor, Department of Mechanical Engineering) and **Dr. Basavanand M Dodamani** (Professor, Department of Water Resources and Ocean Engineering), for their beneficial suggestions and productive remarks that helped improve my research. My heartfelt gratitude goes to **Dr. Ravikiran Kadoli**, Professor and Head, Department of Mechanical Engineering, NITK Surathkal, **Dr. Shrikantha S. Rao,** and **Dr. Narendranath S.** Former Heads, Department of Mechanical Engineering, NITK Surathkal for their consistent support and encouragement throughout my research work.

My heartfelt gratitude goes to **Dr. Premkumar G**. Sincere appreciation is extended to the associates of my parent institution. I must express my gratitude to the team behind my doctoral research, **Mr. Chandrashekara M. K.**, In-charge IC Engine Research Laboratory, **Mr. Jayantha A.**, In-charge Fuels Laboratory, and **Mr. C. A. Verghese**, In-charge Machine Shop for their valuable support. I would also thank the technical staff of IC Engine Research Laboratory, **Mr.Vinayaraj M. K.**, **Mr. Vishal Kumar**, **Mr. Yathin Devadiga**, and **Mr. Yashpal**, and the support staff, **Mr. Ashok K**. I thank **Mr. K. Nishan** and **Pradeep** from Machine shop for the timely response to my research requirements.

My stay at NITK has been enriched through interaction and intimacy with my friends and fellow research scholars. I must acknowledge the help and assistance I got from my fellow research scholars, **Mr. Jayashish Pandey, Dr. Nuthan Prasad B. S.**, **Dr. Libin P. Oommen**, and **Mr. Kishorebabu Bhumula**, **Mr.Madan.K, Mr.Balanagouda N Choudari, Mr. Shripati G M, Mr.Vashista G A, Mr. Anteneh Wogasso**, and **Mr. Addisu Frinjo.** I must thank **Mr. Prakash** from Mangala cold storage, Bikampadi, for his assistance in developing the fuel line in test rig. Apart from the technical support, I must thank my fellow friends **Mr. Madhgonda Biradar**, **Dr. Praveen T. R.**, **Dr. Shashi Kumar C. M.**, **Dr. Thippeswamy L. R.**, **Dr. Banjara Kotresh**, **Dr. Shankar Kodate**, and **Dr. Tabish Wahidi**. I also thank **Mr. Santhosh K** for the healthy discussions.

The doctoral research would not have been completed smoothly without the emotional support of my loved ones, particularly my wife, I honestly acknowledge the unconditional support of my dear wife **Mrs. Dr. Yashashwini T**, who looked after our family and allowed me to relax. **Samrat M D** and **Rohith Mourya M D**'s smiles and naughty pranks always relieved my tiredness and fatigue. I'd also like to express my gratitude to my parents, Late **Mrs. Honnamma D** and Late **Mr. Hanumanthappa R**, for their blessings and encouragement. I'd like to express gratitude to my parents-in-law, **Mrs. Indramma S** and **Mr. Thimmappa T**, for their support, blessings and love. I am thankful to be a part of such a wonderful family. I must express my gratitude to our entire family. **Mr. Ranganath H, Mrs. Saroja, Mr. Govindappa, Mr. Anandamurthy M H, Mrs. Netra R, Mr. Shivanna H, Mrs. Onkaramma H, Late Mrs. Annapurna H, Mrs. Meenakshi M H, Mr. Krishnamurthy T, Mr. Gaviyappa M H, Mrs. Reka, Mr.Dr. VishwanathSagar, Mr.Dr. Bhanuprakash, Mrs.Madhura, Mr. Babu, Yashashwini, Pranathi, Prajval, Hamsa, Likith, Ganavi, BhanuPrakash, Thilak, Dimpana** for their unconditional support. I also want to thank my grandmother, Late **Mrs. Gangajji**, who always encouraged me to study and instilled in me responsibility and moral values.

I acknowledge with gratitude to all others who have helped directly or indirectly in completing my thesis successfully.

DINESH M H

MARCH 2023

ABSTRACT

The environmental effects of fossil fuel combustion in engines have prompted research into the use of carbon-free and low-carbon alternatives. Extensive research indicates that the world's most challenging problems, such as energy costs, energy security, and climate change, can be effectively addressed by sustainable and alternative energy sources. Several nations conduct valuable research to fulfil their environmental responsibilities through decarbonization. Transportation accounts for a significant share of global energy consumption. These engine fuels are derived from hydrocarbons. Hydrocarbon fuels are hazardous to the environment. Therefore, it is necessary to use low-carbon and carbon-free alternative fuels in internal combustion engines with minimal modifications. Therefore, there is significant international interest in the development of methanol, ammonia, and hydrogen as energy storage mediums for automobiles.

Under WOT conditions, the experimental study is carried out in two stages. In the first stage of methanol/LPG, only one phase, the first phase, the influence of variable CR from 12 to 15 is investigated at varying blending ratios from 25% to 45% (LPG) at speeds (1400 rpm to 1800 rpm) while the IT is kept constant at 20ºCA bTDC. The results are examined based on a trade-off between BTE and NOx emissions, and an appropriate operating parameter is determined. In the second stage, ammonia/hydrogen, there are three phases. The first phase containing the influence of variable CR from 12 to 15 is studied at varying blending ratios from 5% to 21% (hydrogen) at speeds of 1400 rpm and 1800 rpm, while the IT remains constant at 24ºCA bTDC. A suitable operational parameter is determined based on a trade-off between BTE and the analysis results. In the subsequent phase, the effect of varying from IT 32ºCA bTDC to 18ºCA bTDC at the blending ratio determined in phase 1 is examined. The appropriate IT and CR are selected for the subsequent stage. In the final stage, various EGR ratios (ranging from 5% to 20%) are investigated for NOx reduction with minimum power loss.

In the first stage of the first phase, methanol/LPG showed a rise in BTE with increase in CR from12 to 15 at an ignition timing of 20ºCA bTDC, according to the performance evaluation. With a compression ratio of CR14 to CR15, the experimental data indicate that a SI engine fuelled with methanol/LPG operates smoothly and achieves favourable results. BTE is almost unchanged for CR14 and CR15. Lower-energy-content methanol produces less power than gasoline when the LPG fraction is below 35%. In this instance, methanol/LPG is operated with a higher compression ratio, which significantly impacts the increase in power output compared to a lower CR. However, P_{max} and HRR_{max} are improved when CR, blending percentage, and speed increase. Undoubtedly, methanol's lower carbon content is expected to produce fewer emissions of carbon. In addition, the in-cylinder temperature was decreased, thus contributing to the reduction of NOx emissions.

In the second stage of the first phase, the performance evaluation suggests that ammonia/hydrogen showed improvement in BTE at CR15 and 21% hydrogen fraction with the ignition timing of 24ºCA bTDC. Increasing the percentage of hydrogen from 5% to 21% enhances combustion. Consequently, the slow-reaction properties of NH_3 are improved. The addition of hydrogen raises the peak temperature; consequently, NOx continues to increase with increasing hydrogen despite the reduction of ammonia. Hence, exhaust after treatment required. During the second phase, the advanced ignition timing improves BP and BTE to a maximum at 28ºCA bTDC. Up to 28ºCA bTDC, the rate of increase in CP and HRR approaches that of TDC. The ignition advance significantly increases NOx emissions at all speeds and CR. BTE is efficient at 28ºCA bTDC and CR15 -16.

The methanol/LPG and ammonia/hydrogen-fuelled SI engine compete equally with the gasoline-fuelled SI engine at a relatively higher CR, advanced ignition, and NOx management via EGR implementation. It was a deliberate endeavour to secure energy resources and provide a realistic option for environmentally friendly transportation technologies. It also implies an enormous opportunity to produce and distribute low-carbon and carbon-free alternative fuels.

Keywords: - *Methanol/LPG and ammonia/hydrogen Fuelled SI Engine, Variable Compression Ratio, Blending Ratio, Variable Ignition Timing, EGR, NOx Control*

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NOMENCLATURE

A/F	Air-Fuel Ratio
ARAI	Automotive Research Association of India
BMEP	Brake Mean Effective Pressure
BP	Brake Power
bTDC	before Top Dead Centre
BTE	Brake Thermal Efficiency
CA	Crank angle in degree
CA10	Crank angle travelled corresponding to 10% fuel mass burnt
CA10-90	Crank angle travelled between 10% to 90% fuel mass burnt
CAGR	Compound Annual Growth Rate
cc	cubic centimetre
CDI	Capacitive Discharge Ignition
CFR	Cooperative Fuel Research
CI	Compression Ignition
CP	Cylinder Pressure
CR	Compression Ratio
DAQ	Data Acquisition System
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
FFV	Flexible Fuel Vehicles
FT-IR	Fourier Transform Infra-red spectrometer
g/kWh	gram per kilo-watt-hour
IAHE	International Association for Hydrogen Energy
ICE	Internal Combustion Engine
IEA	International Energy Agency
IOCL	Indian Oil Corporation Limited
IT	Ignition Timing

LBV	Laminar Burning Velocity
LPG	Liquefied Petroleum Gas
lpm	litres per minute
MBT	Maximum Brake Torque
MGT	Mean Gas Temperature
$NHRR_{max}$	Maximum Net Heat Release Rate
NO_x	Oxides of nitrogen
PEM	Proton Exchange Membrane Analysis
PFI	Port Fuel Injection
P_{max}	Maximum Cylinder Pressure
RDSO	Research Design and Standards Organization
RGF	Residual Gas Fraction
RON	Research Octane Number
rpm	Revolutions per Minute
RTD	Resistance Temperature Detector
SI	Spark Ignition
TDC	Top Dead Centre
T_{max}	Peak Cylinder Temperature
TPS	Throttle Position Sensor
WHEC	World Hydrogen Energy Conferences
WOT	Wide Open Throttle
η_{vol}	Volumetric Efficiency

CHAPTER 1

INTRODUCTION

The increasing population raises fuel demand to drive the automotive sector. Currently, the transportation sector is primarily dependent on petroleum-based fuels, hence, the challenges are alternative fuels for fossil fuels due to depletion, the global crude oil crisis, and rising fossil fuel prices. The dominance of hydrocarbons in the automobile industry produces anthropogenic emissions that impose economic burdens and environmental damage, and also posing a variety of hazards to human life, which are the significant challenges the world faces in the twenty-first century. Hence, most major economy, including India, have committed to net-zero carbon emission goals. Using a holistic framework, this study seeks to identify solutions that can improve climate change reduction and air pollution control by reducing carbon emissions without compromising engine efficiency. To ensure environmental sustainability for present and future generations, we must employ alternative and sustainable energies; however, political will is the biggest impediment to any action. Today, achieving global independence from carbon-based fuels is a priority that is growing in importance. Hence, the global substitution of low carbon and carbon-free alternative fuels and electric vehicles are two successful techniques for decarbonization in internal combustion engines. But due to limitation of electric generation from fossil fuels is the issue as of now. The Renewable and alternative indigenous, non-polluting, and nearly limitless fuels are the most realistic option because they do not demand costly engine modifications. Only a few compounds created from air and water can function as chemical energy vectors. Hydrogen, ammonia, and methanol are three major contenders. As a result, methanol, ammonia, and hydrogen fuels are the most practical transportation alternatives, and further study is needed to utilize these fuels.

This chapter focuses on the physical and chemical properties of methanol/LPG and ammonia/hydrogen fuels in SI engine combustion. Further highlighted on the production and utilization of methanol and ammonia. LPG and hydrogen have good combustion capabilities and have been utilized as methanol and ammonia ignition promoters, respectively.

1.1 Background

Non-renewable sources of energy have been collected in the interior of the earth for millions of years, and gasoline derived from petroleum products has been used in internal combustion engines. As fossil fuels, around 11 billion tonnes of crude oil are consumed annually. According to analysts, if we continue in this manner, our oil reserves could be depleted near future. However, the global consumption of fossil fuels is not constant; as the population and standard of living rise, the price of crude oil increases. Internal combustion (IC) engines used fossil fuels, which led to substantial advances in the use of hydrocarbons beginning in the early 1860s. Fossil fuels are frequently employed in the automotive sector; hence they act as linchpins. For decades, numerous researchers have worked to optimize IC engines.

Whatever the human race discovers, the economy, society, and environment will be impacted. Numerous researchers play a crucial role in developing internal combustion engines. Nicholas Otto (1876) and Rudolf Diesel (1892) invented the Spark Ignition (SI) engine and the Compression Ignition (CI) engine, respectively. Vehicles using fuels derived from petroleum are susceptible to releasing air pollutants. However, industrialized nations, urban centres, and densely inhabited regions are the main contributors to air pollution, causing bad local environmental conditions and significantly impacting human health. However, liquid fuels are still the best option for transportation due to the high density of petroleum fuels, the ease of storage, and the worldwide transport infrastructure established over the past century. However, the current method of providing the world's energy needs, which relies on fossil fuels, does not appear sustainable. The supplies of fossil fuels are depleting, and their combustion products are generating several problems, such as the depletion of the ozone layer, the greenhouse effect, environmental pollution, and acid rain. The number of vehicles on the road increases (According to statistics from the International Organization of Motor vehicle Manufacturers for the 20th century, vehicle demand and manufacturing expanded dramatically as a result of industrial globalization Figure1.1), their gasoline demand increases, and the fuel mix continues to expand with an increasing number of alternatives. Developing an engine using alternative and sustainable fuels to minimize pollution and improve efficiency, consume less crude oil, and lessen energy is currently and will be challenging in the future. Thus, it requires extra emphasis.

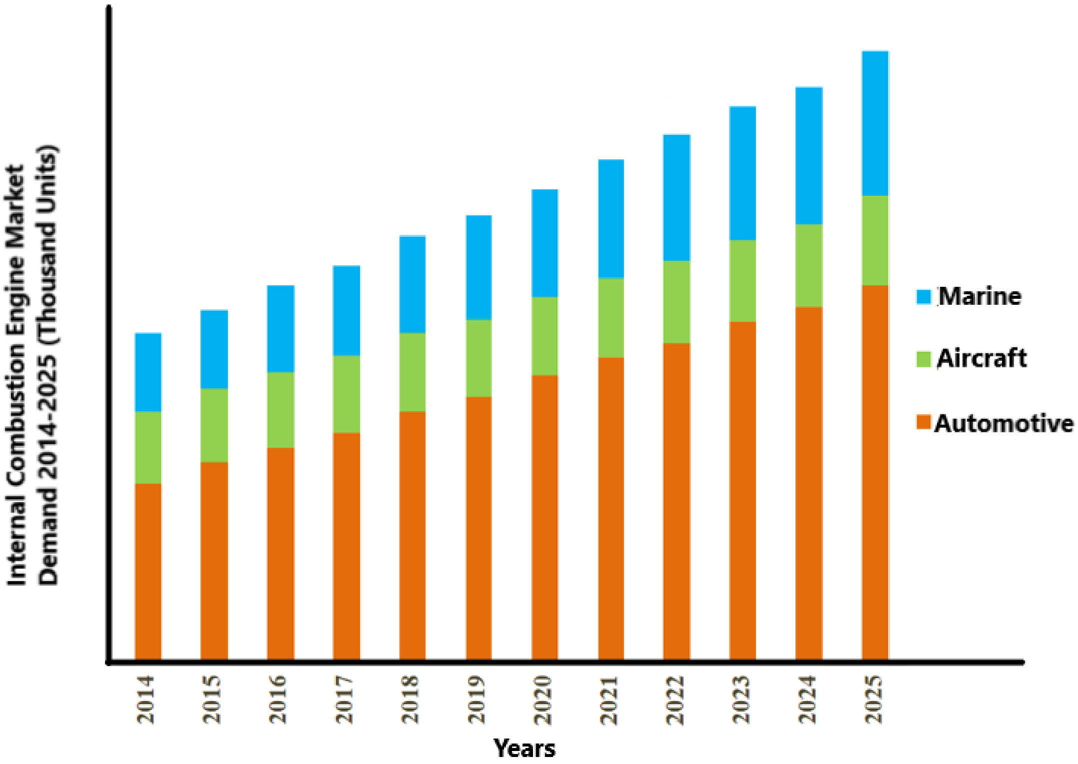


Figure 1.1 IC engine demands in various segments (Sathish Kumar et al. 2022)

Energy is a necessary aspect of economic progress. Each sector contributes uniquely to the economy. Agriculture, industrial, transportation, commercial, and residential energy inputs are all expanding globally. Consequently, energy consumption is a significant factor in the overreliance on fossil fuels such as coal, crude oil, and gas (Dwivedi et al. 2011).Currently India is the third highest energy consumer in the world. After considering India's current and future population and GDP growth, the energy demand is rising substantially. Since the 1970s, the worldwide energy demand has doubled. Energy production and use are firmly bound to all aspects of planned development—each indicator of development links to energy use. Environmental expenses are a part of each nation's economic development. Energy is necessary since it plays an essential role in human growth. Civilization faces two significant hurdles: delivering reliable and affordable energy to a growing population and reducing or eradicating the potential environmental impacts of climate change. Sustainable energy production is our top priority to offer everyone reliable, efficient, and advanced energy.

Several policy measures will be implemented by adopting sustainable and alternative energy systems to decrease or prevent greenhouse gas emissions. In the present and future, the search for and use of alternative fuels that promote sustainable development, preserve energy, increase efficiency, and are compatible with environmental protection will be of increasing significance (Agarwal 2007).

In the 1990s, the growing concentration of greenhouse gases (GHG) in the atmosphere became a global concern. Hence, it has considerably increased interest in alternate, sustainable, clean automotive fuels. Scientists are interested in employing alternative and sustainable fuels in engines since the key goals of the present and future years are to safeguard the environment and provide energy security. Hence, dual-fuel engines can operate effectively with even low-quality, low-calorific-value fuels and offer numerous advantages in fuel efficiency and emissions since they employ two distinct alternatives or sustainable blends more efficiently. Alternative and sustainable fuels promote fuel independence while also decreasing greenhouse gas emissions. These enhance the accessibility of internal combustion engines in conjunction with gasoline and diesel. In today's spark-ignition engines, however, electronic fuel injection systems are utilized instead of carburettors to control the mixture's performance and reduce pollutants.

Consequently, it contributes significantly to the automotive sector regarding engine efficiency and emissions control. Alcohols, hydrogen, ammonia, CNG, and LPG are considered effective fuels in dual-fuel engines and they can be blended with gasoline. Ethanol, methanol, and butanol are the most frequently combined alcohols. Butanol (C_4H_9OH) includes four carbon atoms and isomers, whereas methanol (CH_3OH) contains one carbon atom and ethanol (C_2H_5OH) has two carbon atoms (Pearson and Turner 2014).

Nuclear energy, wind energy, solar energy, and hydro-energy were rarely utilized to replace fossil fuels (Su et al. 2013). In contrast, methanol, LPG, hydrogen, and ammonia were the most significant replacement fuels for SI engines. Methanol, also known as methyl alcohol or wood alcohol, was discovered in 1823. It is a colorless, odorless, and slightly flammable properties. LPG is an ignitable mixture of light hydrocarbons consisting predominantly of 70% propane and 30% butane in liquid form. LPG is colorless, odorless, and denser than air in most cases. It is a non-toxic, lead-free, and non-corrosive cleaner energy source commonly used in home cooking. Hydrogen is an odourless, colourless, and low-density gas that is non-toxic. It is abundant in nature but only in compound form. Atoms consist of a non-neutronic nucleolus holding one proton and one electron. Regular gas is diatomic, consisting of two hydrogen atoms that share an electron and are bonded together. Hence, the lowest possible molecular weight for the hydrogen is 2. NH_3 is a colorless gas with a widely recognized pungent smell. NH_3 is produced by both natural and human sources, such as the decomposition of plant matter and animal waste, and when burned produces H_2O and nitrogen. Ammonia, like hydrogen, is one of the most promising carbon-free, sustainable electro fuels. In addition, ammonia is totally recyclable because it can be generated from abundant nitrogen and water, and its combustion creates the same quantity of water and nitrogen. The alchemist first used ammonia in the early 8th century. The use of ammonia as a fuel in an IC engine enhances or promotes combustion.

Methanol can currently be derived from natural resources and waste streams or by combining recycled carbon dioxide and renewable hydrogen, resulting in lower greenhouse gas emissions than methanol derived from fossil fuels. Due to its energy-generating qualities and safety features, methanol has a long history of use in racing vehicles (slower burning, low heat generation, and burns with fewer emissions). Methanol has been utilized successfully in non-racing automobiles. There was considerable interest in using methanol as a gasoline blend unit in the United States due to its high-octane rating and lower emission characteristics after the gradual elimination of lead from gasoline and the establishment of stringent emissions requirements. Even though no manufacturers have manufactured M100 methanol-compatible vehicles, there are currently 16,000 M85-compatible automobiles on the road, particularly in California and New York. There are additional methanol-powered automobiles in Atlanta, Denver, Detroit, and Houston. In the 1960s, experiments conducted by the U.S. Army on slightly modified IC engines indicated near-theoretical performance if the fuel was partially dissociated so that the input gas contained around 1% hydrogen.

Ammonia is a synthetic compound that can be thermally, physically, chemically, or biologically generated from fossil fuels, biomass, and other renewable sources. It is a clean fuel producing ammonia from any renewable energy source, e.g., solar, utilizing water, biomass, or organic waste and air as main components is possible the history of ammonia used in transportation is shown in Figure 1.2. Shell Chemicals produced NH_3 from natural gas for the first time in 1931, indicating a significant milestone in the synthesis of ammonia. Beginning in 1970, as a result of the natural gas crisis, ammonia makers began to focus on improving and developing ways of producing ammonia from alternative fossil fuels, notably coal. It is also interesting to note that ammonia has an octane rating between 110 to 130. Ammonia is used in vehicle applications as a fuel, refrigerant, and NOx reduction agent simultaneously (Dincer 2008). Europe has researched ammonia as a fuel for IC engines. Ammonia has been studied as an alternative energy source since 1905 when the first study was conducted. In 1935, Ammonia Casale Limited was thought to have conducted the first limited-scale application of ammonia as a fuel.

In 1942, the Gazamo process, a second, more thorough application, was tested on cars in Belgium. In the 1960s, the NH_3-powered X-15 rocket plane set speed and altitude records. The General Motors Research Laboratories were given the task of researching ammonia as a fuel for SI reciprocating engines. In the summer of 2007, a vehicle powered by ammonia and gasoline drove across the United States from Detroit to San Francisco. Toyota has submitted a patent related to the combustion of 100% ammonia that uses plasma jet igniters and a spark plug to prevent the need for H_2 as a fuel promoter and facilitate the ignition of ammonia. The International Energy Association (IEA) has published a comprehensive report on industrial renewable energy consumption techniques. According to the analysis, ammonia is one of the most attractive energy carriers with substantial economic benefits. IEA targets to achieve carbon neutrality in the energy sector by 2050 (International Energy Agency 2021). A healthy global economy must consider fossil fuel dependence's environmental and security consequences. As a hydrogen carrier, ammonia could meet many worldwide requirements for clean, sustainable, and cost-effective transportation fuel in the twenty-first century.

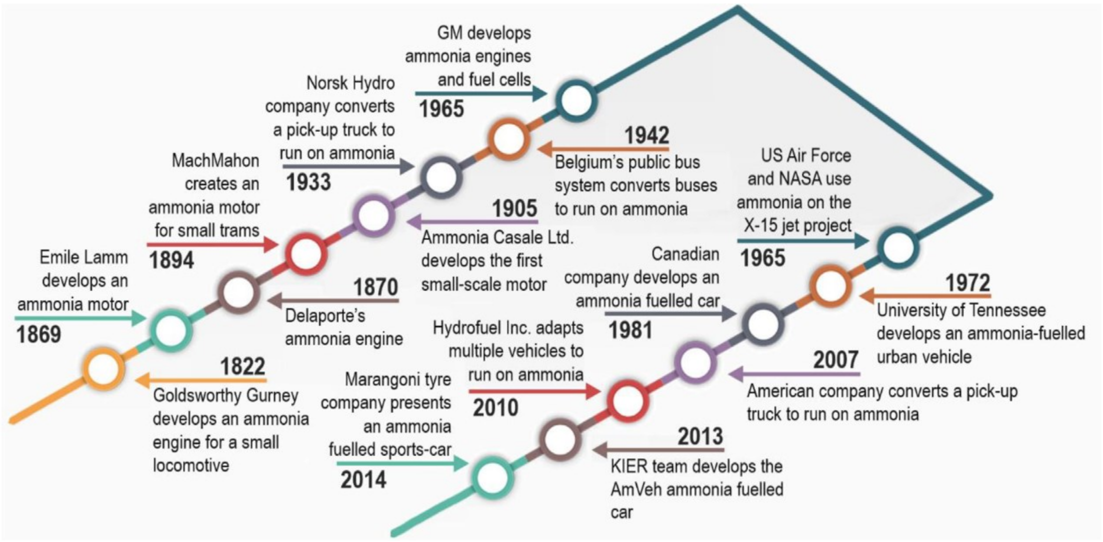


Figure 1.2 The history of ammonia uses in transportation (Cardoso et al. 2021)

1.2 Need for a sustainable and alternative source of energy

More research is required to increase understanding and commercialization, developing more sustainable and alternative energy sources. Appropriate government policies are required to promote the development and supply of low-carbon and no-carbon fuels that are both clean and inexpensive. The study of sustainable and alternative fuels and their applications has become an interesting issue since it reduces reliance on fossil fuels and transportation expenses. As a result, the inevitable depletion of fossil fuels has increased international leaders' worry about future energy security. The current energy conversion processes that utilize fossil fuels significantly contribute to global warming and climate change. New concepts and ideas for energy conversion systems are required to reduce man-made anthropogenic greenhouse emissions and need to protect our environment (Ranger et al. 2012; Rogelj et al. 2011). Researchers and energy professionals have unanimously concluded that sustainable alternative low-carbon and carbon-free energy sources could provide a long-term solution to the impending energy crisis. The Energy Policy Act of 1992 defines the following fuels as alternative fuels: ethanol, methanol, and other alcohols; mixtures of 85% or more alcohol with gasoline; liquid and gaseous fuels domestically obtained from natural gas; propane; coal-derived liquid fuels; hydrogen; ammonia; electricity; pure biodiesel (B100); fuels composed of organic materials other than alcohol. In addition, the U.S. Department of Energy may identify other fuels as alternative fuels if they are primarily non-petroleum, generate considerable energy security benefits, and provide significant environmental benefits. Alternative fuels and electric vehicles are the two most prominent suggestions for sustainable energy sources. There are two types of electric vehicle technology, fuel cell and battery-powered vehicles, which use sustainable energy sources such as solar and wind for electricity (Pollet et al. 2019).On the other hand, electrical vehicle technology requires a significant change from the current IC engine technology, an expensive effort. Therefore, during the transition stage, sustainable and alternative energy is considered a viable option (Verma et al. 2021). Using sustainable and alternative fuels in transportation can simultaneously solve energy availability and air pollution.

In the 1970s, alternative fuels became popular due to energy scarcity. Most alternative fuel vehicles are compatible with traditional fuels such as gasoline (alternative liquids and gas fuels) and diesel (biodiesel and other gas fuels). These automobiles are typically referred to as bi-fuel, dual-fuel, or flexi-fuel automobiles. Researchers have identified biofuels as the primary renewable energy source replacing depleting fossil fuel reserves. Due to their favorable physical and combustion properties, alcohol fuels, such as ethanol, methanol, and butanol, and gaseous fuels, such as CNG, biogas, hydrogen gas, production gas, ammonia, and LPG, are generally accepted as alternative fuels for SI engine vehicles.

The most promising carbon-free fuels with possible future applications in energy systems are ammonia and hydrogens. Hydrogen has a great deal of potential as a carbon-free economy booster, but transportation, storage, and infrastructure limitations prevent its widespread use. In fact, ammonia appears to be an efficient energy carrier with a high energy density and an existing, adaptable infrastructure that can compensate for hydrogen's inherent deficiencies. This established infrastructure, together with the possibility of manufacturing ammonia from renewable energy sources, motivated researchers to investigate ammonia as a feasible future fuel choice for IC engines.

Different individuals in the political, industrial, and social sectors continue to demonstrate global knowledge that a significant change in direction is required to ensure a sustainable future. Various individuals are ahead of others in planned strategies. However, they all appear united by goals such as net-zero emissions of greenhouse gasses and access to renewable energy. Hydrogen, mainly green hydrogen, will play a crucial role in this transition, as the future energy situation will require increasing energy from renewable sources.

As the production and utilization of fossil fuels continue, environmental damage and scarcity of energy are developing as issues. The best way for the transport sector to achieve "carbon neutrality" is to conduct research on energy-efficient technologies and develop novel alternative fuels. The most important chemical product in the world, ammonia, is a potential carbon-free fuel with more combustion energy. It can be used as an alternative fuel to reduce carbon emissions due to its proven production method, low manufacturing costs, safe storage, free of carbon-containing compounds in its emissions, and recyclability.

Currently, ammonia (NH_3) is being investigated as a sustainable energy carrier. The synthesis of ammonia from the gasification of nitrogen-rich biomass is a sustainable, distributed, and flexible approach to the efficient storage and conversion of renewable energy (Wang et al. 2022). Alternative fuels are essential for meeting future emission goals and decreasing dependency on fossil fuels. Currently, biofuels and other so-called sustainable fuels are the most viable long-term solution, although ammonia and hydrogen are also being investigated.

1.3 Methanol and Ammonia economy

According to IEA 2022 sources, the daily demand for Petrol and Gas/Diesel in India is 767 and 1633 thousand barrels per day, respectively; India is the 3rd largest energy consumer in the world and accounts for 5.01 percent of global oil demand. In February 2022, India will contribute 0.72 million barrels per day to global oil production. India's CO_2 emissions in 2022 are 6.83 percent of the global total. Consequently, a situation has emerged in which countries must address both air pollution and energy demand. India, the third-largest emitter of carbon dioxide from energy sources, plans to implement stringent emission standards and reduce crude oil imports by 10% by 2022.

Methanol is a low-carbon, high hydrogen-carrying fuel produced from coal with high ash content, agricultural waste, carbon dioxide from thermal power plants, and natural gas. Methanol can replace gasoline and diesel in the transport (road, marine, and rail), energy (particularly Diesel generators, tractors, boilers, and commercial trucks), and retail cooking sectors, despite its somewhat lower energy content. Blending 15%

methanol with gasoline can reduce the import of gasoline/crude oil by at least 15%. In addition, this would reduce greenhouse gas emissions in particulate matter 20%, NOx, and SOx, thereby improving the quality of the atmosphere's air.

The methanol economy will create nearly 5 million jobs through methanol production/application and distribution services. Moreover, blending 20% DME (a methanol derivative) with LPG can save Rs 6000 crore per year. As a result, the client will save between Rs 50 and Rs 100 for each cylinder. The Bureau of Indian Standards has approved a 20% DME/LPG blend, and the Ministry of Road Transport and Highways has approved M-15, M-85, and M-100 mixes. Test criteria and plans for the M-15 blend are being developed in collaboration with the IOCL, ARAI, and Society of Indian Automobile Manufacturers. RDSO intends to combine methanol at concentrations ranging from 5 to 20% in the railroad industry through direct fuel injection in locomotives. A joint venture with Israel is planning to build five methanol plants using high-ash coal, five DME plants, and one natural gas-based methanol production facility with an annual capacity of 20 metric tons. Cochin Shipyard Limited is building three boats and seven cargo vessels powered by methanol for the Inland Waterways Authority of India.

The double-digit increase in methanol market demand has posed a formidable supply challenge. A market study named "India Methanol Market Study, 2011–2025" forecasts that the methanol market in India will expand at a CAGR of 7%. The production and use of methanol in India are still developing, but the country has enormous potential given its coal supplies and other resources. Despite having a production plant, India imports methanol to meet its need; currently, imports account for 90% of the market. Comparing the liquid hydrogen and methanol vectors for the transportation sector reveals approximately identical fuel costs and energy efficiency, while methanol has significant infrastructure advantages (Specht et al. 1998).

National Hydrogen Mission policy implementation on green hydrogen and green ammonia will reduce reliance on fossil fuels and crude oil imports. India's global commitment to mitigate climate change includes five significant announcements, one of which is to achieve 50% of the country's energy required with renewable energy sources by 2030. Hydrogen offers India and its decarbonization goals potential. It could play a significant role in encouraging renewable energy and decarbonizing tough-to-regulate sectors. However, the government and businesses have already taken the basic steps toward developing an economy based on hydrogen. An essential demand is to maintain momentum through future collaboration. Hydrogen energy is anticipated to cut carbon emissions, projected to increase by 1.5 billion tonnes in 2021. According to the International Renewable Energy Agency (IRENA), hydrogen will account for 6% of global energy consumption by 2050. According to the Hydrogen Council Report for 2021, global expenditures on hydrogen will account for around 1.4% of total global energy funding by 2030. Therefore, carbon-free ammonia (hydrogen carrier) fuel is the most practical alternative for hydrogen. According to India's national hydrogen mission, hydrogen and ammonia are future fuels and will replace fossil fuels in the following decades. Using renewable energy sources to produce these fuels is one of the essential needs for the nation's energy security to be environmentally sustainable. These are referred to as Green Hydrogen and Green Ammonia.

Hydrogen and ammonia are expected to replace fossil fuels in the future. Hence, the Ministry of Power recently notified the first part of the National Hydrogen Mission policy on green hydrogen and green ammonia, which states that green hydrogen and green ammonia manufacturers will be exempt from interstate transmission fees for 25 years for projects financed before June 30, 2025. 2020, 144 million metric tons of ammonia will be produced globally. India's annual ammonia usage for fertilizer manufacture is approximately 15 million tonnes, and approximately 15% of this need (more than 2 million tonnes per year) is now satisfied by imports (Li et al. 2021). China produces around 32.6% of the world's ammonia, followed by Russia (8.1%), India (7.6%), and the United States (6.6%). The manufacturing of ammonia uses both conventional and renewable energy sources. The demand for ammonia has been rising exponentially. The ammonia market is expected to expand within the next decade by around 3% and be categorized as one of the primary fuel sources (Bicer et al. 2016).

Adopting renewable energy, including the mutual conversion of methanol, hydrogen, and ammonia, as well as the adaptive management of energy systems, requires immediate action. In addition, the economy of methanol, hydrogen, and ammonia has grown significantly, particularly in terms of their integration into the energy system.

Renewable energy conversion to methanol, hydrogen, and ammonia (renewable ammonia) is essential due to its favorable qualities.

1.4 The necessity of Methanol, LPG, Ammonia, and Hydrogen

Biofuels can quickly provide a viable response to the global petroleum issue by providing a sustainable economy, energy conservation, as well as environmental protection. Demand for sustainable and alternative fuels is prompted by stringent pollution regulations, decreasing conventional fuel stocks, and a growing economic burden. The most desirable quality for an alternative fuel that is now required is that it be limitless or renewable. In this regard, methanol, hydrogen, and ammonia have attracted significant attention from researchers worldwide, as well as the support and interest of various governments. Due to the scarcity of fossil fuels, building an engine that operates on alternate and sustainable fuels is imperative. Unlike conventional gasoline and diesel, alternative and sustainable fuels are often clean fuels in engine combustion.

Governing organizations propose and approve global strategic plans for sustainable energy development, employing methanol, ammonia, and hydrogen as energy carriers. Solar, wind, and biomass, renewable and sustainable energy sources, make up a significant portion of the available energy sources and provide a substantial amount of electricity. The utilization of methanol, ammonia, and hydrogen in transportation and energy generation has expanded due to technological advancements in their production and storage. All of these factors contribute to a reduced reliance on non-renewable fossil fuels and a diversification of energy sources. Utilizing methanol, ammonia, and hydrogen has some technical challenges that are now being resolved through research. These can be burned effectively in ordinary IC engines with minimal design modifications. Methanol, ammonia, and hydrogen's feasibility as engine fuels relies on their sustainability, economic viability, and the fulfillment of various operational limitations.

Methanol is a recognized source of sustainable energy. In the perspective of carbon neutrality, the low-carbon generation of methanol fuel and its use in IC engines to reduce emissions is of key importance. Methanol is an appealing alternative fuel; it is regarded as the most advantageous fuel compared to fossil fuels. Methanol has recently been used in internal combustion (IC) engines as an alternative to fossil fuels to improve efficiency and reduce emissions. Hence, This is because both environmental and economic concerns are addressed (Zhen and Wang 2015). In spark-ignition engines, it is common practice to use LPG as an alternative fuel to gasoline. Hence, LPG used as a primary driving force because it is less expensive for end users and has low pollutant emissions, so LPG has become increasingly popular as an IC engine fuel. LPG can be regarded as a very appealing fuel (Masi 2012). Without a doubt, spark-ignition engines have evolved over the last 20-25 years, and emissions and fuel economy standards remain stringent. These stringent rules have impacted every stage of LPG technology development (Raslavičius et al. 2014).

The rising market for fuel cells has boosted interest in three sources with a high energy density: methanol, ammonia, and hydrogen. Moreover, these fuel cells represent a potentially significant technological advance for addressing climate change and achieving energy security goals in the transportation, industry, and power sectors. Methanol and ammonia will play a distinct role in the future as hydrogen carriers. Methanol, ammonia, and hydrogen, fuel cell technology can reduce the operational flexibility required to attain fossil fuel dependence in the transportation sector and combine with one or more renewable energy sources to power the system. Numerous technologies are still in their beginnings and have yet to establish themselves in the marketplace. The high cost of production and market demands is a challenge for fuel cell technology. Governments are promoting the research and innovation of a fuel cell based transportation system by providing financing, and various researchers are attempting to establish an efficient fuel system.

1.5 Production of Methanol, Ammonia, and Hydrogen

Processes for manufacturing methanol, ammonia, and hydrogen have evolved from simple industrial to commercial-grade industrial synthesis. These can be produced using carbon-based feedstocks or a carbon-neutral cycle. Hence, we discussed very few production methods, as shown in Figures 1.3,1.4 and 1.5.

1.5.1 Methanol synthesis from CO_2

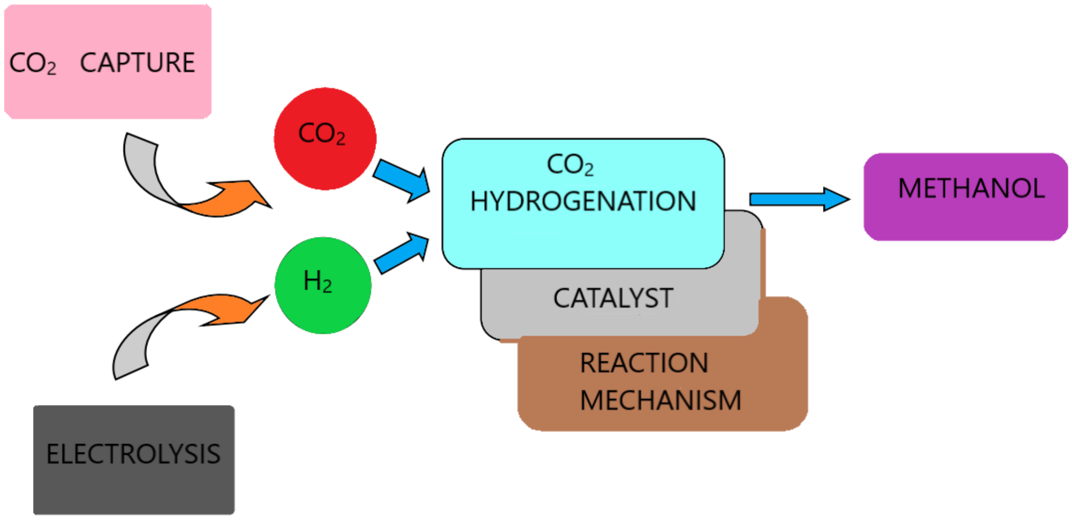


Figure 1.3 Synthesis of Methanol from CO_2

When there is an important need to recycle carbon and decrease CO_2 emissions, converting CO_2 to methanol is proved to be an efficient method of CO_2 usage. In addition, abundant CO_2 availability is a significant feedstock for manufacturing chemicals, fuels, and other essential materials. The process cycle involved in the formation of methanol from carbon dioxide is depicted in Figure 1.3. The catalytic regeneration process, which utilizes CO_2 and H_2 to generate methanol, is one of the first techniques. (Olah et al. 2009) conducted a study and recommended numerous ways to produce methanol and its derivatives and applications.

Sustainable development benefits the generation of methanol from carbon dioxide. The synthesis of methanol from carbon dioxide and hydrogen requires two steps (Gao et al. 2020).

Methanol Synthesis: $CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$ Eq. 1.1

This method makes use of carbon dioxide readily available in the atmosphere, and hydrogen is obtained by water electrolysis. Methanol is hydrogenated either via catalytic regenerative conversion using hydrogen or the electrochemical reduction method.

1.5.2 Production of Ammonia from conventional and renewable energy sources

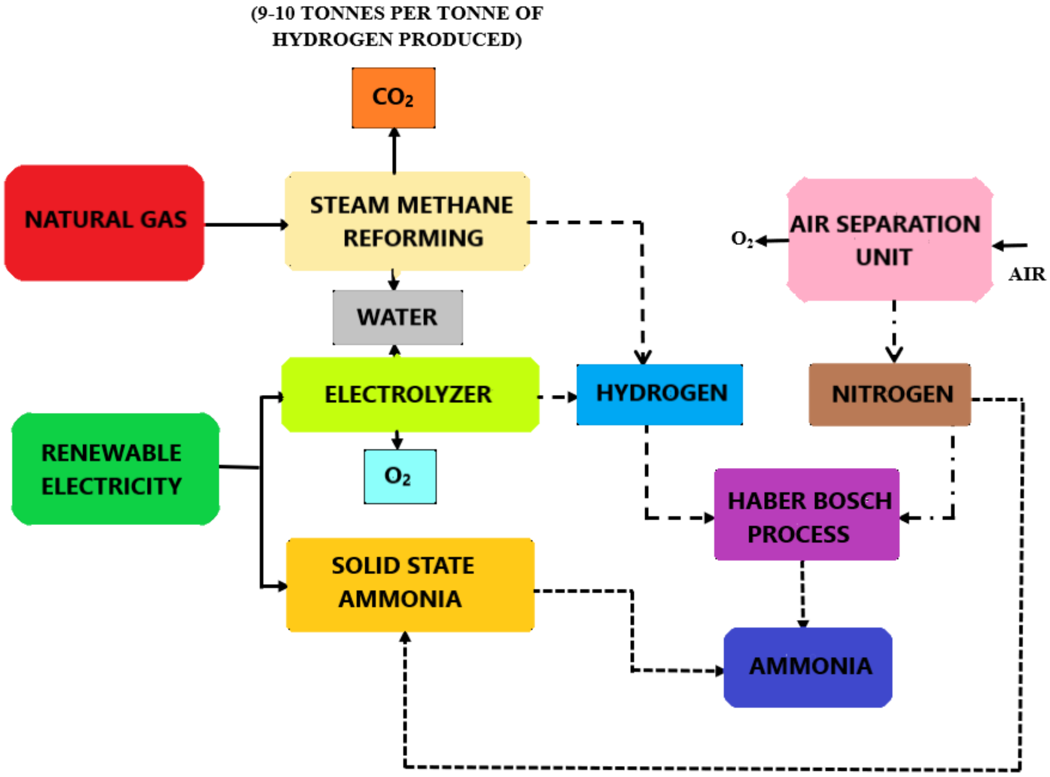


Figure 1.4 Schematic representation of processes involved in the production of ammonia

Typical ammonia manufacturing techniques include Haber-Bosch and solid-state ammonia synthesis (SSAS), as shown in Figure 1.4. The air separation procedure provides the system with nitrogen. Cryogenic air separation is commonly considered as one of the most efficient and cost-effective methods of delivering large amounts of oxygen and nitrogen. This technology can also produce nitrogen gas with a better purity level at a lower cost. Compared to all other air comparison methods used for ammonia production, the cryogenic air separation process is the most industrialized, as it produces ammonia in bulk at a lesser cost and with greater efficiency. Even though the cryogenic process is the most industrialized for ammonia production, the Haber-Bosch technique is still the most popular. At temperatures and pressures of 450-600 °C and 100-250 bar, hydrogen and nitrogen are mixed in a 3:1 ratio to produce ammonia in an exothermic reaction. For the Haber–Bosch process, the subsequent thermo-catalytic reaction is formed.

$$\frac{3}{2}H_2 + \frac{1}{2}N_2 \rightarrow NH_3 + 45.2\frac{kJ}{mol} \qquad \text{Eq. 1.2}$$

SSAS is another way of producing ammonia. An electrochemical solid-state technique creates ammonia from nitrogen, water, and power. Compared to other approaches, SSAS is more energy-efficient, meaning it consumes less energy. The Haber-Bosch combination with electrolyzer costs around 12,000 kWh/tonne-NH_3 compared to 7,000 – 8,000 kWh/tonne-NH_3 for the SSAS process (Yapicioglu and Dincer 2019).

1.5.3 Hydrogen production from PEM electrolysis of water

Figure 1.5. shows the fundamental concept of the PEM (Proton Exchange Membrane Analysis) water electrolysis reaction.

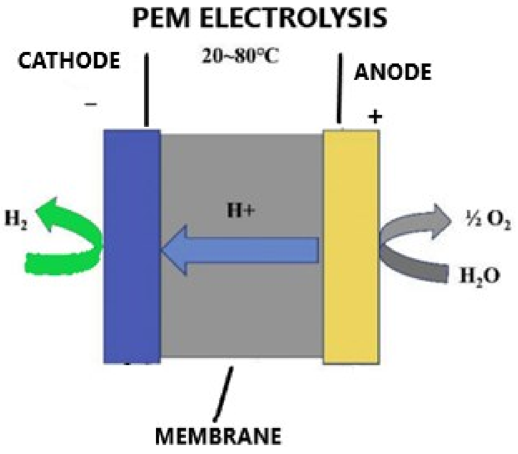


Figure 1.5 Schematic diagram of PEM electrolysis water.

The electrolytic cell is filled with highly purified water. It can be separated into a cathode chamber and an anode chamber by a proton exchange membrane; the electrodes are put in each chamber. At a specific voltage, the current flow across the two poles, with the cathode producing hydrogen and the anode producing oxygen. It addresses the disadvantages of alkaline electrolysis, but there are only a few producers of PEM. Following reactions occur for hydrogen production from PEM electrolysis of water (Zhang et al. 2022).

Anode: $H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^-$ Eq. 1.3

Cathode: $2H^+ + 2e^- \rightarrow H_2$ Eq. 1.4

Total reaction: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$ Eq. 1.5

1.6 Physical and chemical properties of Methanol, LPG, Ammonia, and Hydrogen relevant to engines

Anyone researching an alternative to IC Engine fuels will find methanol's properties interesting. The ratio of hydrogen to carbon is second only to methane among all organic fuels. The oxygen availability reduces the amount of air needed for stoichiometric combustion; hence, more fuel may be burned with the same airflow. Extremely high heat of vaporization compared to other fuels is responsible for cooling the instream air. It may be viewed from two perspectives: first, the cooling of the instream contributes to an increase in volumetric efficiency, and second, it is known for generating combustion issues under idle and cold conditions. Similarly the high autoignition temperature and octane number of methanol, on the other hand, give a chance to increase the compression ratio (CR), which can partially compensate for the cold start disadvantage. As methanol has relatively low heating values compared to any normal fuel, the most effective strategy to alleviate the methanol restriction is to combine it with a highly volatile fuel with a large energy content. Methanol has superior properties than any other fuel, including laminar flame speed, adiabatic flame temperature, flammability limit, and quenching distance. As a fuel for IC engines, methanol indicates both CI and SI engines; however, its low cetane number not suitable for CI engines. However, the research octane number (RON) and the motor octane number (MON) are exceptionally high, making them suitable for SI engine fuel. In addition to a very high-octane rating, a short quenching distance allows the flame to get closer to the cylinder wall, hence increasing the combustion efficiency. Although the lower flammability limit for methanol is quite high, the wide flammability limit enhances the lean burning limit. Furthermore, the high hydrogen-to-carbon ratio of methanol reduces CO_2 emissions per unit of fuel mass. In addition to reducing the engine's peak temperature, the high latent heat reduces NOx emissions despite the engine's high thermal efficiency.

Methanol is commonly blended directly with gasoline, which increases its energy content at the expense of its emissions as a substance with a low heating value. Since gasoline is a mixture of saturated and unsaturated hydrocarbons, its emissions are extremely high; however, it is possible to reduce these emissions by combining methanol with a similar fuel. As a mixture of only saturated hydrocarbons, LPG appears to possess the most advantageous properties of all available fuels. LPG has a greater heating value than gasoline, despite its stoichiometric air-fuel ratio being more than double that of methanol. Similar to gasoline, the autoignition and adiabatic temperatures are close.

LPG, like methanol, has a relatively low carbon to hydrogen ratio, which significantly reduces carbon emissions. Methanol, like LPG, has a low volumetric energy density; however, at the stoichiometric air-fuel ratio, methanol has a higher in-cylinder energy density than gasoline. As a result, the methanol/LPG blend produces a comparatively higher energy density in the cylinder than gasoline. Due to the fact that the flame speeds of methanol and LPG are faster than those of gasoline, a greater mass fraction is burned per cycle, which increases thermal efficiency and decreases specific fuel consumption (SFC). The methanol/LPG mixture, regardless of its composition, has a high-octane rating.

As self-ignition is undesirable in this instance, the compression ratio of the SI engine is limited based on the autoignition temperature of the fuel. Consequently, the CR limit can be increased proportionally to the autoignition temperature. Fortunately, both methanol and LPG have a high autoignition temperature, which necessitates increasing the CR, which aids in reducing the methanol's starting difficulties. However, as a gaseous fuel, LPG decreases volumetric efficiency, which is partially compensated for by a higher CR. In contrast to its effect on performance, the increased CR has an effect on emissions by increasing combustion temperature and promoting NOx production.

Hydrogen carrier-ammonia is a desirable fuel for internal combustion engines with carbon-free footprints. Due to its higher-octane rating, ammonia has been the most researched alternative fuel for spark-ignition engines. With 1.5 moles of hydrogen per mole of ammonia, or 107 kg H_2/m^3 of liquid ammonia at 25°C and 9 bar, there are more hydrogen atoms per ammonia molecule. Ammonia has emerged as a potential carbon-free, sustainable fuel with a higher volumetric energy density and a lower energy unit cost than hydrocarbons and hydrogen. It has a gravimetric density of hydrogen of 17.8%. Compared to hydrogen, liquid ammonia held at 9 bars and room temperature significantly reduces storage tank size and cost; ammonia-based hydrogen storage is one of the possible solutions. The high heat of vaporization reduces the input manifold temperature and the mean cylinder temperature, thereby cooling the instream air and increasing volumetric efficiency due to the "cold burning" of ammonia, which decreases heat losses during combustion. Using identical quantities of stoichiometric air-fuel mixtures, the heat content of an ammonia-air mixture is about 80% of that of a gasoline-air mixture. Compared to gasoline, the lower flame of ammonia marginally reduces peak pressure, resulting in lower cylinder pressure. In addition to the low flame speed, high minimum ignition energy, low flame temperature, and narrow flammability, a powerful combustion promoter improves the stability and performance of the combustion process. The use of carbon-neutral fuels, such as ammonia-hydrogen, in the IC engines of environmentally friendly vehicles has been proposed. Hydrogen is an excellent ammonia additive because it eliminates the cold start problem, thereby improving the combustibility of ammonia.

Hydrogen's high molecular diffusivity increases mixture homogeneity and, therefore, combustion efficiency. Due to their high autoignition temperature and octane number, ammonia/hydrogen mixtures have superior knocking resistance, enabling a higher compression ratio, enhancing thermochemical properties such as pressure and temperature, and enhancing engine efficiency. Increasing the proportion of hydrogen in a flame tends to increase its stretch sensitivity. Adding hydrogen increases the initial concentration of H free radicals during combustion. It stimulates the rapid synthesis of OH free radicals, thereby enhancing the combustion quality of mixed fuel and accelerating NH_3 utilization. In contrast, adding the hydrogen energy portion optimizes it, enhancing the engine's overall combustion efficiency. The high starting ambient pressure decreases the laminar burning velocity of the ammonia mixture, which can be increased by the addition of hydrogen, hence affecting NOx emissions.

Table 1.1. Physical and chemical properties of Gasoline, Methanol, LPG, Ammonia, and Hydrogen (Cardoso et al. 2021; Chiong et al. 2021; Kurien and Mittal 2022; Morganti et al. 2013; Movileanu et al. 2020; Tang et al. 2021; Verhelst et al. 2019).

Fuel Property	**Gasoline**	**Methanol**	**LPG**	**Ammonia**	**Hydrogen**
Molecular weight (kg/kmol)	107	32.04	44	17.03	2.016
Fuel Density (kg/m^3)	741	792	530	0.73	0.08375
Hydrogen Content by mass (%)	~14	12.58	18.2	~18	100
Carbon Content by mass (%)	~86	37.48	18.2	-	-
Lower heating value (MJ/kg)	42.90	20.09	46.4	18.8	120
Higher heating value (MJ/kg)	48.00	22.88	51	22.5	141.9
Flammability limits (vol.%)	1.47-7.6	6.7-36	2.15-9.6	15-28	4.7-75
Research Octane Number (RON)	80-98	108.7	109.2	>130	>130
Motor Octane Number (MON)	81-84	88.6	89	120	120
Volumetric Energy Content (MJ/m^3)	31746	15871	24446	11300	4700
Stoichiometric AFR (kg/kg)	14.70	6.5	15.7	6.04	34.3
Autoignition temperature (K)	553	738	728	924	809
Adiabatic Flame Temperature (K)	~2275	2143	2250	1800	2100

Quenching distance (mm)	2.0-3.0	1.85	1.68-1.8	-	0.6
Laminar flame velocity (mm/s)	425	500	455	15	351
Boiling Point (°C)	35–200	64.8	-42	-33.34	-252.7

1.7 Thesis structure

This study presents the experimental investigation conducted to evaluate the performance, combustion, and emission characteristics of the SI engine operating with methanol/LPG and ammonia/hydrogen blends for improved outcomes. The experimental trials consist of two sections. The first section examines various methanol/LPG blends for fuel, while the second consists of working with an ammonia/hydrogen blend with few operational modifications. This section provides a chapter-by-chapter overview of the entire work.

Chapter 1: starts with a discussion of the current energy demand and the increasing supply and production crisis. It is continued with a quick introduction to methanol, LPG, ammonia, and hydrogen, a viable alternative for sustainable energy sources, and its future viability. In addition, it provides an overview of the sector's historical context, various manufacturing techniques, application areas, effects on the global economy, and current situation. The primary focus is on using methanol, LPG, ammonia, and hydrogen as IC engine fuels and their physical and chemical properties.

Chapter 2: provides an overview of the literature review completed for this research study. This section contains various study resources pertaining to methanol/LPG and ammonia/hydrogen and their use during the previous few decades. In addition, it emphasizes the technological progress that occurred throughout this time period. Typically, methanol/LPG and ammonia/hydrogen fuelled internal combustion engines work with little operating modifications and modified engine parts. Consequently, a brief description of the effect of operating factors on engine characteristics, including the blending ratios, compression ratio, spark ignition timing, and EGR procedures, along with the relevant references, is provided here. The review examines several techniques for using methanol/LPG and ammonia/hydrogen as combustible fuels in internal combustion engines. In the end, the research gap is highlighted, followed by the objectives of the present research.

Chapter 3: provides the experimental approach, systematic experimental work plan, and experimental setup preparation. It provides a concise description of the equations used for calculation and the equipment required to construct the test rig.

Chapter 4: summarises the experimental results and possible reasons. It contains the results of the various experimental trials, with appropriate explanations. Changes in operating settings and their effects on engine performance and emissions are examined in depth. Possible causes for the observed outcomes are examined, and references to helpful suggestions are supplied. The study conducted to examine the potential of methanol/LPG and ammonia/hydrogen as IC engine fuels through various trials is addressed methodically, and a thorough analysis of the data has been performed.

Chapter 5: concludes the purpose of the research work. It provides a satisfactory explanation of the given research and its favourable outcome as well as limitations. Finally, it highlights the scope of future study and the prospect of collaborative multidisciplinary research.

CHAPTER 2

LITERATURE SURVEY

This chapter presents the review reports from numerous sources, such as international journal articles, conference proceedings, and book chapters about the specified topic and study field. Before beginning this task, the thorough study findings and helpful suggestions from the research publications were reviewed. The study focuses primarily on recognizing the usage of methanol/LPG and ammonia/hydrogen as combustible fuels for internal combustion (IC) engines, thereby offering the possibility of reducing dependence on petroleum fuel sources. This study focuses primarily on decarbonizing and improving combustion efficiency.

2.1 History of Methanol, LPG, Ammonia, and Hydrogen as alternative transport fuels

According to research (Küüt et al. 2011), alcohol has been used as a fuel in the transportation industry since the discovery of the IC engine. In the nineteenth century, European agricultural machinery was powered by internal combustion (IC) locomotives fuelled with ethanol. This is what two prominent scientists, Otto and Ford, find so fascinating.

From 1979 to 1982, the German Alcohol Fuel Research Program was initiated. The Federal Minister for Research and Technology provided funding for German automakers, universities, and research institutions to focus on using a 15% methanol blend in petrol engines and evaluate its efficiency (Menrad and Nierhauve 1983).

The development of alternative-fuel vehicles reportedly began in the 1970s (Nichols 2003). The government has long been interested in enhancing air quality and fuel security. Experimental fleets of methanol vehicles performed well in the automobile industry, but a refuelling infrastructure shortage led to the FFV's development, a gasoline or methanol vehicle. Ford enacted legislation in 1993 to commence production of the M85 FFV and advance the car industry.

Sustainability is essential in alternative fuels. According to (Yang and Jackson 2012), Nobel laureates George Olah and co-workers have advocated for over a decade that combining fossil-based fuels and chemicals with methanol and methanol products is an excellent approach to long-term sustainability. China has already taken this direction's initial step. China plays a significant role in producing methanol, and dimethyl ether (DME) derived from coal, and its prices are reasonable to those of fossil fuels. Methanol's outstanding properties might give several benefits to the transportation industry. Ola believes the methanol market is essential for a sustainable future because low-carbon content methanol is manufactured from recycled carbon dioxide and biomass. It is a reasonably established technology that is easier and less costly to produce than ethanol made from cellulose. China's production of methanol from biomass reduces net greenhouse gas emissions.

According to (McNicol et al. 1999), the history of the direct methanol–air fuel cell is neither as long nor as famous as that of the hydrogen-air fuel cell, which was initially shown in 1839 by William w x Grove and, more recently by the late Francis.w x Tom Bacon. Bacon's work culminated in deploying hydrogen-air fuel cells in the apollo space program. Shell Research in England and Exxon-Alsthom in France invented the direct methanol–air cell in the 1960s and 1970s. After initial trials with sulfuric acid, Exxon-Alsthom selected the alkaline electrolyte option, while Shell opted for an acid electrolyte and employed sulfuric acid.

CO_2 and hydrogen are used to generate methanol, according to (Anicic et al. 2014). Carbon dioxide-based methanol synthesis is a new technique, and until recently, only a handful of pilot-scale facilities existed. There are two techniques used to convert CO_2 to methanol. The first approach involves directly synthesizing methanol from carbon dioxide and hydrogen, while the second method requires two steps. In the first step, a reverse water-gas shift reaction partially converts carbon dioxide to carbon monoxide, and a further mixture is supplied to the methane reactor in the second stage. Hence, this is achieved by the CAMERE (Carbon Dioxide Hydrogenation of Methanol by Reverse Water Gas Shift) technique. The two-stage procedure is crucial since carbon dioxide is the least during direct synthesis.

The Indian government has also supported the methanol industry by keeping it under the NITI ayog and assisting farmers in producing green methanol. One of the primary reasons for methanol's consideration as a fuel is the variety of its production techniques; secondarily, the fuel's liquid nature makes it simple to transport. China produces 70%

of its methanol from coal, as its coal reserves are the third largest in the world. Other nations, including the United States, South America, and Iran, make methanol mostly from natural gas because to its wide availability and low cost. India can follow in China's footsteps, as our country has the fifth-largest coal reserves in the world and, if utilized well, can considerably contribute to the production of methanol and DME (Saraswat and Bansal 2017). The government is willing to pursue a goal of 15% DME/methanol blending in diesel/gasoline by 2022, which, if reached, could result in savings of approximately $8 billion by 2022.

According to (Snelgrove et al. 1996), LPG, often known as Autogas, is a naturally clean energy source for transportation. LPG generally relates to compounds with three to four carbon atoms. The principal source of commercial LPG is natural gas. Depending on the processing and refinement of petroleum, the structure of industrial LPG may vary substantially from nation to nation. Winter and summer can be distinct from one another. In order to produce gases with sufficient vapor pressure, colder regions in Europe are often home to a higher percentage of C_3.

In contrast, warmer climates are likely to be accompanied by increased C_4 levels. Its market penetration of car fuels has relied mainly on tax benefits related to gasoline and the development of a distribution system. Due to the economic benefits of gaseous fuel, environmental issues have gained a considerable deal of attention in recent years. Technological developments for gaseous-fuelled vehicles, factory-made new vehicles/engines and different nations cars have collaborated to expand the market potential of LPG.

LPG, ethanol, and CNG can be utilized as alternative fuels in IC engines (Bayraktar and Durgun 2005). Liquefied Petroleum Gas is a highly promising fuel for internal combustion engines because of its lower cost, higher calorific value, high RON, and cleaner emissions. LPG can be manufactured from natural gas, which can be called a renewable fuel that is more efficient and produces lesser emissions than gasoline. Numerous studies have examined the performance and emission of vehicles that run on pure LPG and LPG blends.

Ammonia, like methanol and LPG, has the potential to be used as an alternative fuel. According to (Cornelius et al. 1965), General Motors Research Laboratories evaluated ammonia as an engine fuel in favour of the energy storage concept suggested by the Allison Division of General Motors Corp. The purpose of the energy storage concept is to eliminate the military's dependence on hydrocarbon fuels. The generation of energy from water and air is one approach. Among the potential fuels that could be manufactured, ammonia (NH_3) was deemed to offer the highest benefits. A mobile nuclear reactor would provide the energy necessary for synthesizing this fuel. General Motors Research Laboratories evaluated NH_3 as an alternative fuel for SI engines.

According to logistics studies of military activities conducted during the Second World War in Korea (Pearsall and Garabedian 1967), approximately 65% of the required tonnage for combat operations consisted of fuels and lubricants. Future army schemes due to the increase in technology, mobility, and proliferation, the army sought alternative vehicle materials and equipment. It was determined that nuclear power was an apparent option, but the direct application of nuclear power to automobiles posed substantial obstacles; therefore, the focus was then diverted to other prospective nuclear energy applications. According to additional research, the army demonstrated the viability of transportable nuclear reactors as a source of energy on the battlefield via collaborative research and development, either indirectly or directly with energy conversion devices or as a source of energy for chemical fuel production to achieve an early return on investment. It was determined that a nuclear power source would give the necessary energy to produce chemical fuels from air and water. This plan to generate energy on-site is known as mobile energy deportment. The most promising constituents are ammonia, hydrogen, hydrazine, and hydrogen peroxide. Ammonia was selected as the excellent fuel based on its physical and chemical properties and ease of handling, storage, and transportation.

The energy distribution centre idea has generated considerable interest in using ammonia as a transportation fuel (Pearsall and Garabedian 1967). Before engine studies on a large scale, research programs were done to determine the viability of ammonia combustion in different systems and to study potential solutions to specific known difficulties. The University of California investigated theoretical aspects of ammonia combustion, and the U.S. Army Engineer Research and Development laboratories conducted turbine research. The Army Fuels and Lubricants Research Laboratory investigated ammonia's use in SI and CI engines.

Research conducted by the army on ammonia has contributed significantly to the continuation of research. However, ammonia (NH_3) is a high RON fuel that can be substituted for CO_2-emitting fuels in automotive transportation, according to a study by (Mackenzie et al. 1996). It combines with hydrogen the characteristic of producing water and nitrogen solely as combustion by-products when burnt in internal combustion engines. However, it overcomes the storage, safety, and logistical issues associated with using hydrogen fuels in automobiles. Ammonia can be stored at ambient temperatures and low pressure. Its physical properties closely resemble those of liquid propane. It can be stored in a tank appropriate to existing vehicles. There are global infraustructure for its storage, safe handling, shipping, and distribution because it is utilized as a fertilizer in volumes exceeding 100 million tonnes annually. If the anticipated costs of global warming and air pollution produced by fossil fuels should be included in the economic calculation, it could be a cost-effective alternative to gasoline.

A unique study of ammonia scrubbers for carbon dioxide removal from flue gas. (Bai and Yeh 1997) experimental outcomes suggested that NH_3 scrubbing's ability to reduce CO_2 emissions is promising. Under optimal operating conditions, the overall CO_2 removal efficiency may surpass 95%. According to an MEA (Aqueous monoethanolamine) solution, it should be greater than that. X-ray diffraction analysis, scanning electron micrograph images, and pH observations were utilized to determine and analyze the reaction products.

(Árnason and Sigfússon 2000) present a pathway towards a future Icelandic hydrogen energy economy. The government's goal is to increase the usage of alternative energy sources that are friendly to the environment. Producing eco-friendly fuels for use in vehicles and fishing vessels is a viable technique for reaching this goal. Hydrogen is one example of such a fuel. In hydrogen fuel technology, forming a company controlled by Icelandic parties and many corporate executives worldwide could provide new prospects.

(Nejat Veziroğlu 2000) examined the quarter century between 1974 and 2000 and found that hydrogen energy has advanced on all fronts, penetrating all energy-related fields. In this regard, however, researchers, engineers, and visionaries such as WHEC conference attendees and IAHE members have made outstanding contributions. Therefore, a hydrogen energy source could provide the only known habitable planet with the energy system it truly deserves: one that is clean, efficient, sustainable, and provides sufficient power for decades.

Hydrogen has recently been acknowledged as a possible replacement for existing vehicle fuels. (Mathur et al. 2008) examined the economic analysis techniques of hydrogen generation, namely the use of wind energy to produce hydrogen through electrolysis of saltwater, focusing on the Indian transportation industry. The study provides insight on a variety of issues, including the benefits of offshore plants over coastal installations, the economics of large clusters of wind turbines, and a cost comparison of manufacturing hydrogen versus gasoline.

Hydrogen is a flexible fuel that can provide complete independence from the energy (fuel) problem and environmental damage. (Das 2002) outlines certain parts of a set of experimental studies conducted on multiple configurations of a hydrogen-powered engine, with the introduction of hydrogen engines into the current energy infrastructure in mind. Experimentally determined optimal performance, low-emission features, and procedures to eliminate unwanted combustion processes, including such backfire, pre-ignition, knocking, and rapid rate of pressure rise.

2.2 Characteristic study of Methanol/LPG and Ammonia/Hydrogen blends

The adoption of stricter emission regulations and the rising demand for petroleum-based fuels encourage the usage of combustion promoters with fuel sources. This section explains the characteristic study of utilizing dual fuels to enhance the engine's performance, combustion efficiency, and carbon emission reduction or promote a carbon-free environment.

Methanol's fuel qualities, including oxygen ratio, octane rating, latent heat of evaporation, density, viscosity, and laminar flame speed, are superior to gasoline. However, its molecular weight, lower heating value, boiling point, and Reid vapor pressure are lower. These characteristics were studied by (Bechtold 2007) and allowed the use of methanol with a high CR value with reduced ignition advance, enhancing performance, and reducing emissions.

The higher octane number and oxygen content in IC engine fuels have resulted in notable improvements in engine characteristics (Eyidogan et al. 2010). The octane rating is essential to fuel performance in SI engines; it allows a higher CR. Adding methanol enhances the octane rating of the operating fuel, and therefore blends usually perform much better than conventional fuel while increasing the compression ratio (Bilgin and Sezer 2008). (Rankovic et al. 2015) article attempted to provide specific data. His research focuses on constructing the fuel matrix with needed octane qualities. Provide knowledge about a SI engine's octane need.

The current approach replaces oxygenated organic molecules with high octane for lead-based additives. Methanol, ethanol, and butanol are the most often utilized oxygenates as additions for SI engine fuel. Methanol, a high-octane oxygenate chemical substance, has shown substantial performance improvement and decreased emissions to a significant extent. It has an excellent resistance to knock, contains less carbon and also more oxygen, reduces carbon monoxide and nitrogen oxide emissions, and significantly improves combustion characteristics if the engine is modified appropriately (Ai-farayedhi et al. 2016; Awad et al. 2018b).

Mass proportions of carbon, hydrogen and oxygen in methanol (CH_3OH) are as follows: 37.5%, 12.5%, and 50.0% (the stoichiometric ratio of air to fuel is 6.4) (Chen et al. 2021b). Methanol requires less oxygen for complete combustion than gasoline (14.7 air/fuel stoichiometric ratio). The RON of methanol is 109, which is also higher than the RON of gasoline (88–98), allowing it to replace gasoline engines. When alcohols (such as methanol, ethanol, and n-butanol) are used in engines, the octane rating can be increased, engine combustion and emissions can be improved, and engine knock can be avoided (Calam et al. 2020).

According to (Patil, B et al. 2014), LPG is universally recognized as a clean alternative to gasoline and diesel since it includes fewer carbon molecules. Its lower carbon-to-hydrogen ratio minimizes carbon dioxide emissions (CO_2), formaldehyde, and acetaldehyde, among others. Additionally, LPG has a high-octane rating, a high heating value, little carbon accumulation, is simple to store, and is economical. LPG consists of saturated and unsaturated hydrocarbons and is a mixture of commercial butane and propane.

In a single-cycle fuel injection strategy, the effects of room temperature on the firing behaviour and uncontrolled emissions of electronic control inlet port injection spark-ignition methanol as well as LPG, and methanol engines during in the cold start were investigated (Gong et al. 2011) experimentally. With a decrease in room temperature from 301 to 289 K, the minimal amount of methanol injected each cycle ensures the methanol engine's successful ignition increases by 86%. Even with large methanol injection, the methanol engine cannot be appropriately started when the ambient temperature is less than 289 K without additional assistance. In the LPG/methanol engine, the LPG only served as a start-up help. Utilizing additional LPG fed into the input port enables the LPG/methanol engine to start reliably at low room temperature. With an increase in room temperature, the cylinder pressure increases while the unburned methanol reduces noticeably.

LPG enhanced port injection start assistance was utilized to enhance combustion and emission characteristics and eliminate cold start problems for SI methanol engines operating at below room temperature. (Gong et al. 2018) using a cycle-by-cycle control strategy, the influence of injection timing of methanol and LPG added fraction on cold start burning; and hydrocarbons (HC), formaldehyde, and unburned methanol emissions were explored experimentally. The injection timing of methanol substantially affects the cold start firing behaviour of LPG with constant injection timing. During optimal methanol injection timing, methanol reaches the cylinder at the appropriate time for the optimal firing of the subsequent combustion cycle after fuel injection. The addition of sufficient LPG can assure reliable cold start ignition. The methanol engine achieved the lowest HC, unburned methanol exhaust emissions, and the maximum formaldehyde exhaust emission, with optimal methanol injection timing. Increased LPG injection proportion decreased HC and unburned methanol exhaust emissions considerably while rapidly increasing formaldehyde emissions. During injection time of methanol and LPG addition fractions, formaldehyde and unburned methanol tailpipe emissions exhibited opposite trends. However, HC and unburned methanol tailpipe emissions exhibited comparable tendencies during a cold start.

The SI methanol engine seems to cold start problem below room temperature. LPG can be added to a SI methanol engine to ensure an excellent cold-start problem. Based on a single-cycle fuel injection method, the impacts of the amount and injection durations of methanol and LPG each cycle on cold start combustion and emissions of such an LPG/methanol dual-fuel SI engine were (Gong et al. 2019) experimentally studied. The results indicate that the minimal amount of LPG injected each cycle is the deciding factor for reliable ignition in LPG/methanol engines with low ambient temperature. It is possible to employ an injection interval of 300 ºCA between methanol and LPG throughout the combustion cycle to generate an optimum mixture. The fuel injection parameters significantly impact the HC emissions, which seem to be 74.4% lower in critical firing mode compared to misfiring mode. By modifying injection parameters, unburned methanol exhibits opposing tendencies for formaldehyde emissions and equivalent trends for hydrocarbon emissions.

The oxidation of pure ammonia faces numerous obstacles, including significant NOx emissions, high ignition energy, slow reactivity, and reduced laminar flame speeds. Therefore, a mixture of NH_3 and H_2 increases flame stability and speed (Medriat et al. 2021).

Ammonia's energy per volume and energy per mass densities are lower than gasoline by factors of 2.60 and 2.30; correspondingly, they are still well within the range of practicality for use in automobiles. NH_3 can be stored as a liquid at a temperature of 300 Kelvin and a pressure of around 10 bars. The feasibility of combining ammonia with other, more reactive fuels (combustion promoters) to produce satisfactory engine operation was investigated (Grannell et al. 2009). Due to ammonia's excellent knock resistance, the power-to-mass, power-to-cost, and power-to-displaced volume ratios should be superior to those obtained with gasoline alone.

Several performance criteria were analyzed, including system efficiency, fuel tank compactness, driving range, and driving expense (C. Zamfirescu 2009). The cooling effect of ammonia was also included in assessments of ammonia's efficiency. Cooling using ammonia consumes nearly 20% of the engine's power, which is a benefit of having ammonia on board because it allows the engine cooling system to be reduced and air conditioning to be installed. The system's efficacy can be increased by 11% if the cooling effect is considered. As a fuel, hydrogen source, cooling medium, NOx-reducing agent, and potentially a medium for energy storage, ammonia can play a key role in automotive applications. Hence, ammonia is considered one of the future's sustainable hydrogen economy options.

According to research (Duynslaegher et al. 2010), the change in the compression ratio substantially impacts the acceleration of laminar burning velocity. An adiabatic flame temperature changes due to compression and equivalence ratios. Cooling with ammonia consumes up to 20% of the engine's power, The temperature of adiabatic flames was found to increase slightly with compression ratio. Therefore, a variation in compression ratio does not affect the location of the adiabatic flame temperature's maximum value, which is continuously observed at an equivalence ratio of 1.01. (Joo et al. 2012) in general, ammonia substitution increases NOx emissions.

Both ammonia and hydrogen have a more excellent octane rating than gasoline, making a higher CR ideal. A higher CR is desirable because ammonia and hydrogen have a higher-octane number than gasoline. The flame speed and minimum ignition energy for NH_3 and H_2 differ significantly. By combining, it was believed that a satisfactory agreement might be reached. The ratio of NH_3 to H_2 introduces a new engine control parameter. In addition, it is shown that a rise in CR improves the indicated efficiency as well as mean effective pressure. These characteristics are common in SI engines. The most significant result is that combinations containing much hydrogen have the lowest indicated efficiency and mean effective pressure. Hence, this is likely due to the increased hydrogen intake air dilution compared to ammonia. When compared, the results for ammonia/hydrogen mixes and gasoline had an essentially identical indicated mean effective pressure. The increased CR compensates for the decreased airflow caused by the dilution of the intake air. It is highly relevant to the practical application of ammonia/hydrogen mixtures for SI-engine fuel. Increasing the CR makes generating the same amount of power feasible without utilizing a larger engine. In addition to having a comparable power output, ammonia and hydrogen mixtures with a high CR have a much higher indicated efficiency than gasoline with a lower CR. IMEP and efficiency improvements resulted from the CR studied by (Mørch et al. 2011).

Ammonia has a significantly higher-octane number than gasoline. Thus, mixtures of ammonia and gasoline have a more significant octane number than gasoline alone. A higher specific heat capacity in ammonia can assist in lowering the combustion temperature within the combustion chamber, causing a reduction in cooling power. During higher engine speeds, these characteristics can be attributed to the increase in power and torque and the reduction in exhaust temperature. The improved octane number is supposed to minimize engine knocking difficulties. Thus, with ammonia-rich fuels, higher compression ratios are possible. (Dissanayake 2017) When ammonia-rich fuels are compared to conventional fuel, particularly at higher engine speeds, more excellent performance characteristics are obtained.

According to (Wang 2018), whereas ammonia has a lower energy density per unit volume than conventional fuels, its lower A/F ratio mitigates this drawback. Comparing total emissions by mass indicates that the combustion of NH_3 produces much fewer total emissions than hydrogen, gasoline, diesel, methane, or ethanol. Since hydrogen combustion produces no carbon dioxide, its mass-based emissions are much more than those of other fuels and five times more than NH_3 per unit of fuel mass. In addition, the total emissions of both fuels when producing the same amount of combustion heat are comparable. Ammonia is a possible fuel with fewer emissions and high energy efficiency.

Ammonia has a boiling point is -33.35°C and freezing point of -77.73°C, it has considerable potential as fuel in extremely cold conditions. Since the dielectric constant of liquid NH_3 is normally high and its molecule shares the same electron configuration and bond angles as water, it is highly soluble in water. Due to its excellent solubility in water, this substance can be diluted with water to render it non-flammable and lessen the risk of fire or explosion (Astbury 2008).

(Duynslaegher et al. 2009; Song et al. 2016; Xiao et al. 2017) researchers have explored the burning velocity, ignition delay time, and emissions chemistry of NH_3 as significant fuel factors. In addition, the addition of H_2, CH_4, O_2 enrichment level, and preheating temperature also have a good effect on the complete combustion and burning velocity of an NH_3 flame. (Pochet et al. 2019) due to inducing a significant delay in the ignition, fractions of hydrogen greater than 10% volume were required upon addition. A substantial hydrogen reserve or direct ammonia reformation at the engine intake is required, if necessary, acceleration.

LBV is the most significant combustion parameter. In (Wang et al. 2020) experiments, the LBV was evaluated in a vessel with a constant volume at varied equivalence ratios, beginning temperatures, and oxygen concentrations up to the undiluted state. Thirteen of the most recent NH_3 kinetics mechanisms were compared to experimental data. According to the data, many processes' forecasts displayed significant disparities. The maximum LBV for undiluted NH_3/O_2 mixtures could reach 125.05 cm/s. The projected maximum LBV of NH_3/O_2 is nearly double the predicted minimum LBV for NH_3/O_2 mixtures.

Hydrogen is notable among possible boosters because it is carbon-free and it enhances ammonia's combustion properties. Hydrogen has a higher flame speed and a flammability range than NH_3, which has a low flame speed, low flame temperature, high ignition energy, and self-ignition temperature (Stefano Frigo and Doveri 2012). In terms of improving combustion stability for the fuel with the lowest energy density (80% inert gas dilution instance), H_2 addition tests with a stoichiometric excess air ratio were conducted by (Park et al. 2011). Because of hydrogen's rapid flame propagation speed, an increase in hydrogen concentration in the blended fuels improved combustion characteristics, reducing total hydrocarbon emissions and increasing NOx emissions. The stoichiometric combustion testing demonstrated that a moderate proportion of hydrogen improved engine efficiency.

According to (Kornbluth et al. 2010), the favourable combustion properties of hydrogen can improve flame stability when combined with other fuels. The enhanced flame speed from hydrogen enrichment enables combustion to occur more rapidly at a fixed equivalence ratio. In contrast, the wider flammability range from chemical kinetics enables flames to propagate in mixtures containing leaner. Enrichment with hydrogen stabilizes combustion, allowing for ultra-lean operation. Hydrogen has a higher flame speed and greater specific energy, allowing for a shorter burn duration and improved work transfer to a piston in lean and ultra-lean results. Similarly, hydrogen enrichment has been proven to improve brake thermal efficiency.

Hydrogen was supplied to a gasoline SI engine with four cylinders. The percentage of H_2 in the mixed fuel (gasoline + H_2) ranged from 0 to 18% by mass; thus, its inclusion improved engine stability (Ji and Wang 2009). Adding H_2 lean burn limit increased and enhanced thermal efficiency and also output power (Porpatham et al. 2007). Adding small amounts of H_2, like 3-5%, increased thermal efficiency from 33% to 38%. H_2 addition also reduces cyclic variation (Bade Shrestha and Narayanan 2008).

(Sawyer et al. 1968) the percentage of nitrogen oxides produced by the combustion of NH_3/air in a spark ignition engine at a range of fuel-air ratios representative of regular engine operation with NH_3 was examined in a single cylinder. The quantities of nitric oxide exceeded those of hydrocarbons. The outcomes show a different method for nitric oxide generation with ammonia fuel than with hydrocarbons and that an equilibration process may occur during combustion and exhaust, resulting in a decrease in the concentration of exhaust gas recorded. While an ammonia-fuelled engine does not emit carbon monoxide or unburned hydrocarbons in the output emissions (except for minor amounts produced by lubricant combustion), oxides of nitrogen are likely to be a concern—the replacement exhaust gas unit.

(Li et al. 2014) studies the carbon-free fuel viability of H_2 and NH_3. Experiments were conducted to study the combustion properties and NO_x production in the burning of H_2 and NH_3 at various A/F equivalence ratios and beginning H_2 concentrations. With the addition of H_2, the number of H_2 atoms in the flame rose, which boosted the rate of ammonia combustion. The combustion rate of NH_3 might be moderately accelerated and combined with H_2 as fuel for commercial gas engines. H_2 plays an accelerating role in the ignition of H_2–NH_3–air; however, NH_3 significantly impacts the maximum burning velocity of H_2–NH_3–air. Furthermore, fuel-NOx has a significant role in H_2–NH_3–air combustion, whereas thermal-NOx plays a minimal function. H_2–NH_3–air combustion produces less thermal NOx than pure H_2–air combustion. Maximum NOx concentration is reached during stoichiometric combustion. In addition, H_2 is discovered at an air-fuel equivalency ratio of 1.00 for NH_3 combustion breakdown. Therefore, the stoichiometric combustion of H_2 and NH_3 should be carefully studied when H_2 and NH_3 are used as fuels in practice. Using H_2 and NH_3 as prospective fuels for enhancing combustion performance.

To find the impact of H_2 addition on the auto-ignition of NH_3 at high temperatures, ignition delay times of stoichiometric NH_3/H_2 blends were evaluated (Chen et al. 2021a) inside a shock tube at temperatures ranging from 1020 to 1945 K, pressures of 1.2 and 10 atm, as well as hydrogen fractions ranging from 0 to 70%. Seven available kinetic models were compared with the measured ignition delay timings. Using the Glarborg Model and the Otomo Model, chemical kinetic analyses were conducted to evaluate the interactions between ammonia and hydrogen during high-temperature autoignition. Ammonia ignites more slowly than H_2, and adding H_2 can decrease the ignition delay time in a nonlinear fashion.

According to (Wang et al. 2021c), by adding 10 to 50% hydrogen to ammonia, the ignition delay time may be efficiently decreased. The ignition parameters of the blended fuel can be altered by adding 10% hydrogen. The ignition property of the mixed fuel is enhanced by the addition of hydrogen.

2.3 Effect of operating parameters

The port injection of methanol/LPG and ammonia/hydrogen has advantages over carburation. However, the very diffusive fuel still limits air induction. (Açikgöz et al. 2015) investigated the beneficial hydrogen limit experimentally when combined with methane. Even at 20% hydrogen, they identified a significant improvement in brake power; however, even at 30% hydrogen, a significant improvement was recorded. Rapid combustion improved thermal efficiency as well.

2.3.1 Varying compression ratio

Methanol is more resistant to knock and emits fewer pollutants than gasoline. Small engines with a single cylinder, a low compression ratio (CR), and a slightly rich mixture have low power and high emission levels. If these engines are run on fuels with a high-RON, their performance can be boosted at high CR. In the (Çelik et al. 2011) investigation, a high concentration of methanol was utilized to improve the performance and reduce the emissions of a engine. Initially, the engine with a CR of 6 was tested at full load and varied speeds with gasoline and methanol. The CR steadily increased from 6 to 8 and 10. Using methanol, no knock was noticed at the CR of 8 and

10, whereas it was observed at the CR of 8 when using gasoline. They were using methanol with a CR of 6 reduced CO, CO_2, and NOx emissions without a noticeable decrease in engine output. Increasing CR from 6 to 10 using methanol, the engine power and BTE rose by as much as 14% and 36%, respectively. In addition, CO, CO_2, and NOx emissions decreased by approximately 37%, 30%, and 22%, respectively.

They were experimentally tested at 1800 rpm by (Starkman and Samuelsen 1967), and the compression ratio affects flame speed. Variations in compression ratio indicate, among other factors, the simultaneous effects on variations in mixture temperature and density, turbulence, diluted fraction remaining in the cylinder, and the extent of an advanced combustion reaction. When the CR is increased from 6:1 to 10:1, all of these factors contribute to a 30% increase in ammonia flame speed and a 40% increase in average kernel formation time. However, the improvement in flame speed for iso-octane is about 25%. The need to advance the spark for ammonia compared to iso-octane is due to the slower flame propagation.

(Westlye et al. 2013) investigates the N_2-based emissions of a H_2-enriched NH_3-fuelled SI engine. Due to the nitrogen concentration of the fuel, the creation of these pollutants may differ from that of typical HC combustion, necessitating specific consideration. Experiments are conducted utilizing a 0.612l single-cylinder CFR engine with CR ranging from 7 to 15 and a fuel mixture of 80% ammonia and 20% hydrogen. With an FT-IR, wet exhaust samples are examined. Measuring emissions reveals that nitric oxide is produced by reactions other than the dissociation of nitrogen molecules. This causes the NO emissions to peak at approximately 35% rather than the standard 10% excess air for hydrocarbon-fuelled SI-engines. Due to lower flame temperatures, though, its magnitude of NO emissions is comparable to that of measured outcomes with gasoline. Nitrogen dioxide levels are higher than gasoline, but it contributes a comparatively small amount to total NOx emissions (3–4%).

The LBV of NH_3/H_2 mixtures must need between 40-70% hydrogen fraction (based on the equivalence ratio) to achieve the same level as hydrocarbon fuels. In contrast, increasing compression ratio could reduce the required hydrogen fractions (Wang et al. 2021a). Minimum ignition energy exhibits opposing tendencies to LBV well with the addition of hydrogen and requires an even more significant hydrogen fraction to achieve the level of hydrocarbon fuels; however, when CR is increased from 10 to 18, the requirement for H_2 fraction is reduced. Because of the improved performance at higher CRs and strong knock resistance, NH_3/H_2 mixes work better than hydrocarbon fuels at high compression ratios.

Experiments were conducted by (Nuthan Prasad et al. 2020) on VCR SI engine at varied speeds ranging from 1200 to 1800 rpm at 200 rpm intervals under a wide open throttle (WOT) situation. The engine is fed an equal proportion of methanol and gasoline, and the ignition timing of 14 ºCA bTDC is fixed for all three CRs (8, 9 & 10). By increasing the methanol/gasoline blend's CR from CR8 to CR10, the maximum pressure and NHR value at 1600 rpm have improved by 27.5% and 30%, respectively, resulting in an improvement in combustion efficiency. At a compression ratio of 10:1, the performance results indicate a 25% improvement in BTE and a 19% reduction in BSFC. CO and HC emissions reduced by 30-40% at higher compression ratios (10:1), and the same trend was observed at all speeds; however, NOx emissions increased as the CR increased.

Methane, methanol, and ethanol are mainly three alternative fuels with high octane. As fuels for engines with a high CR, they can increase thermal efficiency and minimize knocking. (Li et al. 2022) the investigation examines the performance, combustion, and emissions of a high-CR spark ignition engine fuelled by methane, ethanol, and methanol in detail. A 1-D simulation model of a 4-cylinder SI engine with a high compression ratio has been developed. The engine was modified from a CR17.5 CI diesel engine, and an injector for methanol, ethanol, or methane was put in the engine's intake port. Under the same speeds and equivalence ratios, the BP and BTE of methanol have been higher than those of ethanol and methane; methane had the lowest BP and BTE; methanol had the highest BSFC and BTE; the CO and NOx emissions of methanol were lesser than those of ethanol and methane; the HC and carbon dioxide emissions of methane were lesser than those of methanol.

2.3.2 Varying blending ratio

Light- and heavy-duty vehicles, alternative fuels, and pollution impacts have been the subject of research (Dhaliwal et al. 2000). As a cleaner alternative to gasoline, stringent pollution regulations promote low-carbon and carbon-free alternative fuels. They determined that using methanol (M100) in temperatures below 150°C necessitates a dual fuel method. LPG is also one of the top three feasible alternatives to gasoline in terms of popularity. LPG is more effective than gasoline at reducing total hydrocarbon, carbon monoxide, and hazardous emissions from light-duty vehicles. A mixture of 85% methanol and 15% gasoline reduces overall hydrocarbon emissions in light-duty cars while maintaining CO and NO_X levels comparable to gasoline.

(Ji et al. 2013) investigated the impact of H_2 addition on enhancing the performance of a methanol engine operating under part-load and lean circumstances. The experiment was conducted on a modified SI engine with an adaptive dual-fuel injection system. The engine was operated at 1400 rpm with two hydrogen volume fractions in the intake of 0% and 3%. According to the test results, the injection of hydrogen reduced the cyclic fluctuations of the engine and boosted the BTE. Moreover, the H_2 enrichment considerably decreased flame growth and propagation times. In general, the injection of H_2 decreased HC and CO emissions. High excess air ratios made it possible for the H_2-blended methanol engine to emit low levels of nitrogen oxides.

Compared to mixing NH_3 with CO or CH_4, (Han et al. 2019) report that mixing NH_3 with H_2 is the most effective method for increasing the burning velocity of NH_3-based fuel blends, as the SL values are the highest. Mixing NH_3 with CH_4 is a less effective strategy for enhancing the combustion rate of NH_3-based fuel mixtures.

(Lhuillier et al. 2020) investigated experimental study on the engine performance, combustion characteristics, and exhaust emissions of a recently developed SI engine fuelled with premixed NH_3/H_2/air mixtures. Gaseous NH_3 blends with a wide variety of hydrogen fractions and equivalence ratios were investigated at two different engine loads. When the required promotion strategies are implemented, the outcomes are comparable to conventional fuel operations. In particular, adding up to 20% hydrogen by volume to the fuel improves cycle stability. It eliminates misfires while delivering optimal work output and recommended efficiencies near stoichiometric levels. Due to greater heat loss through the wall, larger hydrogen percentages result in decreased efficiency. The length of combustion is exactly proportional to the LBV of the mixture, therefore adding hydrogen accelerates it. The influence of hydrogen on acceleration is particularly pronounced during the initial phase of combustion. As a result, hydrogen appears predominantly as an ignition booster. Increasing the engine's load boosts output and expands the operational restrictions of the mixture composition.

(Mounaïm-Rousselle and Brequigny 2020) recent findings in existing SI engine combustion chambers revealed that a CR of approximately 10:1 could be adequate to burn NH_3 with minor amounts of H_2 (nearly 5–10 percent volume) or even without H_2 at "full load" for future hybrid vehicles. Adopting NH_3 in all-thermal powertrain vehicles, a variable CR, or increased intake pressure would enable smoother operation with ammonia while minimizing the amount of H_2 produced onboard.

The Nuthan Prasad et al. (2021) investigation of the combination of methanol and H_2 is viewed as meeting both environmental and economical requirements. Methanol's limitations as a fuel will be mitigated by hydrogen with superior combustion properties. In the present experiment, adding hydrogen to methanol significantly improved performance and combustion while reducing overall emissions. The engine is operated at various speeds with wide-open throttle (WOT) conditions for various studies, including H_2 enrichment ranging from 5 to 20% with a 2.5% increment. Increased hydrogen enrichment has led to an increase in BP and BTE and a decrease in BSEC. The increment in Brake thermal efficiency is between 20% and 30%, and an increase in hydrogen over 12.5% would have a negative impact on volumetric efficiency, resulting in a drop in performance. The exhaust emissions significantly affect H_2 enrichment; reduced carbon emissions by 30-40%; however, a rise in cylinder temperature due to fast combustion causes a slight increase in NOx emissions. Therefore, H_2-enriched methanol working at a higher CR can significantly increases the overall engine characteristics.

Various test cases for an outwardly extending turbulent premixed flame structure using pure NH_3 and NH_3/H_2 fuel mixes of 10% and 15% hydrogen by volume for varying equivalence ratio values of 0.90, 1.0, and 1.1 were explored by (Yang et al. 2022). In comparison to stoichiometric and fuel-rich flames, the fuel-lean flames were shown to have more wrinkly structures at the flame front. Adding hydrogen to ammonia increases the flame's reactivity and the combustion process, as indicated increasing in the heat release rate. Compared to fuel-rich instances, fuel-lean examples were found to have the highest turbulent burning velocity findings. The results reveal a blending effect for the ratio of turbulent to laminar burning velocities in connection to hydrogen addition at all equivalence ratios, with a 10% hydrogen addition to ammonia exhibiting the highest value for this ratio.

2.3.3 Varying ignition timing

In a stationary spark ignition (SI) engine with a constant equivalence ratio of 0.92, the effect of adding a modest amount of hydrogen to biogas was tested (Porpatham et al. 2017). The engine's thermal efficiency in the biogas mode was excellent in this condition. A diesel engine with a single cylinder was adapted to function as a SI engine. The CR was 13:1, while the throttle opening remained at 100%. The engine speed was 1,500 rpm. The highest levels of power generation and thermal efficiency were achieved with a 10% hydrogen energy sharing. At 16 ºCA bTDC, the percentage of hydrogen indicates the greatest rise in BP and thermal efficiency. Thus, 16 ºCA bTDC was determined to be the best spark timing.

(Gong et al. 2020) evaluated combustion and lean burn limit of a methanol/hydrogen-fueled SI engine under variable IT. They observed a continuous rise in P_{max} and HRR_{max} with ignition advanced, while the corresponding angle was advanced too. However, increasing hydrogen fraction led to increased and advanced P_{max} and HRR_{max}. CA10 was reduced with ignition advanced to a minimum and then increased while CA90 was reduced continuously.

(Xu et al.2019) studied the emissions of hydrogen-powered engines during the cold-start period. They found that the engine speed increased significantly during the first five seconds when the spark was delayed. However, the CP was first increased from 25ºCA to 15ºCA and subsequently lowered with additional delay during the first cycles. According to reports, the maximum rate of pressure rise increases with spark advance till 15ºCA. CA10 decreased with spark advance until 15ºCA, while CA10-90 was reported to decline continually. It was discovered that NOx emissions rise with spark advance.

(Pandey and Kumar 2022) experimentally, the hydrogen-assisted combustion of an ethanol/butanol mixture of equal volume is evaluated at various CR, ignition timing (16ºCA to 24ºCA bTDC) for three hydrogen fractions (5% - 15%) at three speeds (1400 rpm-1800 rpm). Increasing CR and hydrogen percentages cause an increase in BP, BTE, Pmax, HRRmax, and NOx, whereas CA10-90 decreases. Compared to gasoline, the ignition timing of 20 ºCA at CR15 and 15% hydrogen performed better.

2.3.4 NOx control by EGR

EGR influences flame kernel growth, which has a considerable impact on combustion. It was evaluated on a hydrogen PFI engine (Salvi and Subramanian 2016). Their research revealed that EGR significantly reduced flame kernel expansion. In addition, they noticed an increase in engine knock probability when it is more than the equivalence ratio of 0.80. They concluded that flame kernel growth depends on equivalence ratio and EGR rates.

Determining the EGR rate is perpetually a matter of discussion; researchers use a variety of ideas and techniques to assess it. Because engine combustion primarily depends on composition, the dilution ratio influences it. Some researchers consider air circulation and recirculation, while others focus on oxygen availability. (Verhelst et al. 2012) analyzed various strategies and concluded that relative error increased substantially with decreasing EGR rates across all methods. They determined that the approach based on the oxygen molar mass has the least inaccuracy, while the relative humidity method was ruled out.

(Lee et al. 2014) studied the effects of EGR during lean combustion; they discovered a sudden decrease in NOx with increased EGR but a modest rise with increasing hydrogen content. By utilizing EGR, the length of the combustion was shown to rise while the thermal efficiency decreased. Since methane was the primary fuel, the EGR rate was observed to increase HC emissions.

EGR use reduces oxygen, resulting in more significant dilution, which restricts the fuel's access to oxygen despite its high diffusivity. Therefore, combustion is prolonged, and cooling losses increase, resulting in a decrease in performance. (Yu et al. 2019) had seen the effects of EGR on engine combustion and performance experimentally. They observed a minor initial increase in BMEP (up to 6-18% EGR, depending on the concentration of hydrogen) followed by a significant fall. EGR increased CA10 at all hydrogen concentrations, whereas CoV rose. With the addition of hydrogen, though, it settled down. NOx was reported to decrease with EGR to near 0 at 30% EGR regardless of hydrogen or λ.

2.4 Summary of the literature survey

The entire literature review provides a summary of recent trends, identification of supporting theories, and approaches, source evaluation, and identifying insufficient data or a research gap.

This investigation primarily emphasizes methanol fuel as a potential alternative for diesel and gasoline in internal combustion engines. In the previous decade, methanol consumption has increased by nearly 2.5 times, while production capacity has increased by approximately three times. In a few years, methanol's manufacturing capability may be able to meet global demand and attain mass production, as evidenced by data from the scientific literature.

In addition, methanol is recommended as fuel for IC engines due to its physical and chemical properties. A higher-octane number encourages a greater CR, knock resistance, and downsize; a higher latent heat of vaporization helps in better volumetric efficiency and higher BTE, and a faster flame speed enhances combustion efficiency. Numerical and experimental studies were done to examine SI engines performance, combustion, and emission characteristics fuelled by methanol/LPG or gasoline/gaseous fuels/diesel.

Variable compression ratio, blending ratio, port injection, and flex-fuel operations are among the operational modifications tested. The economic benefits and environmental and health impacts of methanol were discussed. The low carbon concentration of methanol produces less hazardous exhaust gases, while oxygen aids in combustion, hence lowering engine exhaust emissions. Due to methanol's lower heat content, research has revealed that LPG-enriched methanol engines offer superior performance efficiency and combustion. As a mixture of only saturated hydrocarbons, LPG appears to have beneficial properties. LPG has a higher heating value than gasoline, despite its stoichiometric air-fuel ratio being double that of methanol. Similar to methanol, the autoignition and adiabatic temperature values are close. LPG has a higher hydrogen-to-carbon ratio than gasoline, reducing carbon emissions significantly.

Hydrogen promotes combustion in an ammonia/hydrogen-fueled engine due to its high laminar burning velocity, high adiabatic flame temperature, and high quenching effect. Because of the superior knock resistance of NH3/H2 the greater combustion efficiency under higher compression ratios than hydrocarbon fuels, hence, ammonia/hydrogen mixes with a high CR are preferred. The addition of hydrogen lowered the ignition delay and flame development times and boosted the rate of pressure rise and heat release in the cylinder. Ammonia exhibits its slow-reaction nature at low hydrogen percentages, resulting in low BTE despite a rising CR. As the percentage of hydrogen increases, the combustion quality improves, resulting in more efficient fuel combustion and a greater BTE. Increasing CR decreases ammonia's latent effects and ignition lag, resulting in rapid combustion and an increase in BTE. In addition, the increased hydrogen proportion at a high compression ratio reduces the disadvantage of ammonia and the short quenching distance, allowing the flame to approach the cylinder wall. Therefore, a substantial quantity is burned, resulting in a rise in BTE. Using a lean burning approach is another aspect that significantly affects BTE.

Hydrogen's high diffusivity is responsible for its quick mixing with air, but a greater specific volume displaces a significant amount of air in the mixture, hence decreasing η_{vol}. However, the latent effect of ammonia cools the instream charge, resulting in an increase in η_{vol}. The cooling effect of any fuels in the instream air affects the increase in η_{vol}, which results in a greater BTE. Higher octane number and latent heat of vaporization influence engine anti-knocking capability greatly, resulting in proper ammonia combustion despite a lower heating value. Therefore, the BTE can be increased. Higher hydrogen diffusivity increases the homogeneity of the mixture, leading to an increase in fuel conversion efficiency, and the effect of the drop in η_{vol} caused by the use of hydrogen can be mitigated. On NOx generation, the hydrogen addition effect and lean burning conditions predominate. However, NOx emissions are not a concern because, in the event of a stoichiometric mixture, NOx can be successfully reduced by a conventional reducing catalyst, and in the case of a lean mixture, the presence of ammonia on board facilitates the usage of an SCR.

Advancement of ignition timing improves BP, BTE, P_{max}, and HRRmax. It was found that NOx emissions increase as spark advance increases. Hydrogen is a fast-burning fuel with higher autoignition; a slightly retarded ignition helps keep the P_{max} near TDC in the expansion stroke, which improves η_{th}. However, a much-delayed ignition increases EGT and lowers P_{max} resulting in low η_{th}. The CA10 and CA10-90 improve with increasing CR; however, for a rich mixture, CA10 and CA10-90 are prolonged; further increased CR suppresses the flame propagation. However, a delayed ignition reduces CA10 to an extensive range, but CA10-90 improves for a shorter range.

Since T_{max} is reduced by retarding ignition, NO_x emissions are significantly suppressed. Further, with increasing leanness, NO_x could be put down to 0 at the stake of large power loss. Hence, despite a significant reduction in NO_x, the influence is not enough to maintain a healthy limit. On the other hand, EGR is proven far better, reducing NO_x efficiently at the stake of a slight drop in performance. EGR controls oxygen flow and reach, increasing dilution; hence, combustion is prolonged. Due to increased MGT, there is an improvement in combustion for a low EGR rate. Higher EGR rates result in significant dilution and stratification, leading to improper combustion. However, NO_x emissions drop, but efficiency also falls drastically. The permittable limit NO_x can be achieved at a slight performance drop.

2.5 Research gap

This study utilized data collected from a variety of scholarly sources, including historical documents and recently updated open-source articles. As stated in the preceding sections, open-source contains extensive documentation of numerous studies examining the effects of using methanol/LPG mixture, modifying operational parameters when using ammonia/hydrogen mixture, and other applications.

According to the existing literature, the effect of varying various operating parameters, namely CR and blending ratio for the majority of fractional and ignition timing for mixtures in the standard SI engine model, has not been exhaustively studied. However, NOx emission control through EGR during ammonia/hydrogen operation requires extensive work, but no research has been conducted. Very few articles have examined the performance, combustion, and emission characteristics of a variable compression ratio engine fueled by methanol/LPG and ammonia/hydrogen.

The current study demonstrates that methanol/LPG and ammonia/hydrogen fuels can be used in IC engines with minimal modifications. At WOT, performance, combustion, and emissions of a SI engine fueled with methanol/LPG and ammonia/hydrogen were investigated.

These factors motivate researchers to examine the effects of modifying the engine's operating parameters. The final steps involve conveying the intention to use methanol/LPG and ammonia/hydrogen on a large scale, requesting subsidies, and promoting it as a global long-term energy alternative. Consequently, the research gap is filled by defining the project's objectives.

2.6 Objectives of research

Research Objective: Experimental investigation of the performance, combustion, and emission characteristics of low-carbon (Methanol/LPG) and carbon-free (Ammonia/Hydrogen) fuels in a four-stroke single-cylinder SI engine.

Specific Objective:

- Effects of compression ratio and blending ratio (Methanol/LPG).
- Effects of compression ratio and blending ratio (Ammonia/Hydrogen).
- Effects of ignition timing (Ammonia/Hydrogen).
- Optimization of the above parameters.
- Study of NO_X formation and control with EGR(Ammonia-Hydrogen).

CHAPTER 3

EXPERIMENTATION

3.1 Experimental workbench and detailed research methodology

The present experimental work investigates the viability of methanol/LPG and ammonia/hydrogen fuels in a single-cylinder, four-stroke SI engine; it includes a modification recommendation, parameter optimization, and the implementation of performance-enhancing approaches to achieve the desired output. This chapter discusses the apparatus used to achieve the specified objective and the experimental research methodology. In the present study, a single-cylinder four-stroke SI engine using variable compression ratio and blending ratio for methanol/LPG and variable compression ratio, blending ratio, ignition timings, and EGR for ammonia/hydrogen is utilized.

3.2 Details of Methanol/LPG engine test setup

Experiments are conducted on a 661cc single-cylinder four-stroke port fuel injection engine (specifications shown in Table 3.1) adapted from a CI engine, as depicted in Figure 3.1. The cylinder head is modified to accommodate a spark plug, a pressure transducer, and a spark plug wire (PCB Piezotronics, Model SM111A22). The capacitor discharge ignition system is installed with a spur-geared-end flywheel and starter motor in place of the original flywheel. In addition to replacing the cylinder block with a hydraulically liftable one, a stud and bolt mechanism is given for vertically lifting the cylinder block. The intake manifold has a throttle body connected with a manifold air pressure (MAP) sensor and port-fuel injection systems for methanol and LPG. Both injectors are electrically regulated, each equipped with a fuel pressure sensor. The exhaust manifold is equipped with a K-Type thermocouple 185mm from the exhaust valve, and the exhaust line is then connected to a calorimeter of the Shell and Tube kind. The engine crankshaft is attached to an eddy current dynamometer (Make-Technomech, Model- TMEC10) to which a load cell (transducer) is connected. A crank position sensor with just a precision plate is mounted on the crankshaft. On the opposite side, the gas injector is attached to a sequential reducer (Make- Auto Fuels, 1.2bar to 3bar output), keeping injection pressure of 1bar, and a dry-type flame arrestor.

The LPG cylinder is attached to a wet-type flame arrester with a safety valve (Make-ELGI equipment, A020002, 3/8-inch, 1-7bar). Further attached to the supply pipe is an LPG flow meter (Make-ATN, 0-100lpm, minimum count 0.01 lpm). A separate gas ECU controls the gas supply nozzle (Make- Autogas AC STAG 300) that is fitted after the fully programmable core ECU (Make-Performance Electronics, PE3-8400). If the main ECU receives the instruction to keep the methanol injector open for 12 milliseconds, the auxiliary gas ECU likewise enables the gas injector to remain open for 12 milliseconds. The water flow rate to the engine and the calorimeter, two rotameters (Make: Omega, 0-350 lph) are mounted. A data collection (16-bit DAQ, NI-USB-6210) system is coupled to sensors to acquire the data and transfer it to the system, in which a LabVIEW-based program collects the data and analyzes the engine's performance. After the calorimeter, an exhaust gas analyzer (Make: - Indus Scientific Pvt. Ltd., PEA250N) is utilized to analyze the exhaust gas.

Table 3.1 Detailed engine specifications

Model	Kirloskar TV1, water-cooled
Bore	87.5mm
Stroke	110mm
CR	Variable (12:1 to 16:1)
No. of Cylinders	1
Rated Power	4.5 kW @ 1800 rpm
Ignition Timing	Variable (36ºCA bTDC- 0ºCA bTDC)
Electronic Control Unit	PE3-8400

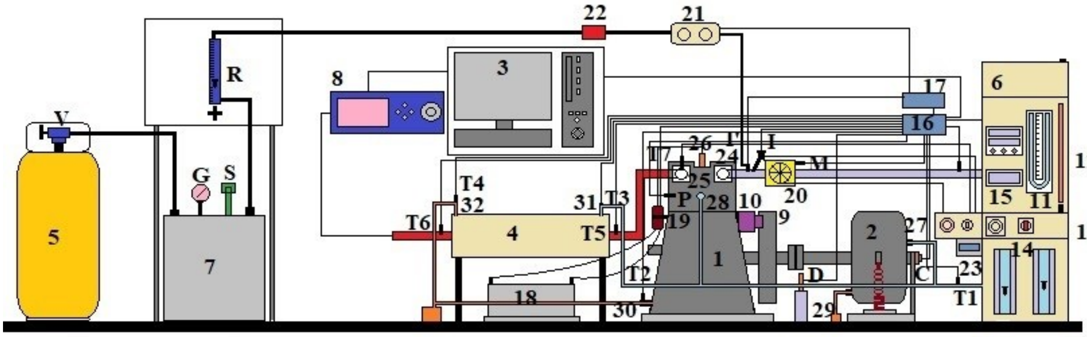


Figure 3.1 Schematic diagram of the engine test set-up (Methanol/LPG)

1-Engine, 2-Dynamometer, 3-Computer, 4-Calorimeter, 5-LPG-Cylinder, 6-Fuel tank, 7-Wet flame arrester, 8-Exhaust gas analyzer, 9-Flywheel, 10-Starter motor, 11-Manometer, 12-Fuel burette, 13-Air-box, 14-Water rotameters, 15-Load knob, 16-Open ECU (main), 17-Gas ECU, 18-Battery, 19-Capacitor, 20-Throttle-body, 21-Sequential reducer, 22-Dry flame trap, 23-T7 display, 24-Inlet-manifold, 25-Exhaust manifold, 26-Spark-plug, 27-Water inlet (dynamometer), 28-Water inlet (engine), 29-Water outlet (dynamometer), 30-Water outlet (engine), 31-Water inlet (calorimeter), 32-Water outlet (calorimeter), M-MAP Sensor, C-Crank encoder, D-Crank position sensor, G-Pressure gauge, P-Pressure Transducer, R-Gas rotameter, S-Safety valve, V-LPG Supply valve, T1-Thermocouple (inlet water, engine & dynamometer), T2-Thermocouple (outlet water, engine), T3-Thermocouple (inlet water, calorimeter), T4-Thermocouple (outlet water, calorimeter), T5-Thermocouple (exhaust gas inlet, calorimeter), T6-Thermocouple (exhaust gas outlet, calorimeter), T7-Thermocouple (Exhaust gas, manifold)

3.3 Methodology for the Methanol/LPG experimental investigation

3.3.1 Plan and procedure

A flowchart provides an outline of the experimental methodology intended for the investigation. Figure 3.2 shows the detailed step-by-step process taken to complete this investigation.

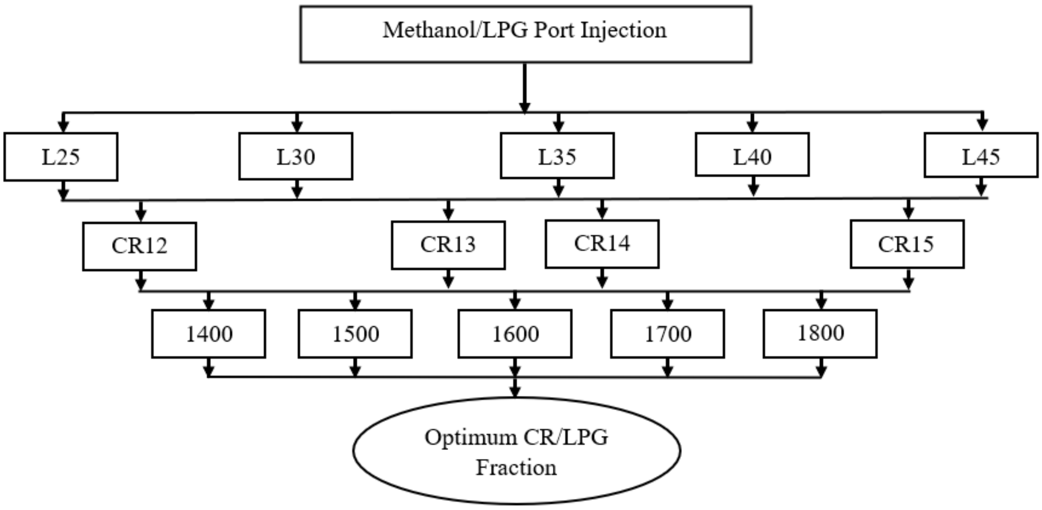


Figure 3.2 Detailed flowchart of a methanol/LPG experimental study

The experiments are conducted under wide-open throttle (WOT) conditions, and ignition time is fixed at 20ºCA bTDC based upon (Nuthan Prasad et al. 2020b) experimental study. Four CRs are investigated from 12 to 15. At each fixed CR, five blend ratios of LPG are used based on energy fraction, from 0.25 to 0.45 for five speeds ranging from 1400 rpm to 1800 rpm. Since methanol has a very low heating value and stoichiometric air requirement, the injection duration is kept maximumly allowable by the ECU, 12mS, which acts as a base to calculate the LPG flow rate.

3.3.2 Calculation

LPG flow rate calculation

$$v_L = \left\{\frac{v_M \times \rho_M \times LCV_M}{\rho_l \times LCV_L}\right\} \times \left\{\frac{x_L}{(1 - x_L)}\right\} \qquad \text{Eq. 3.1}$$

Here, v_M, ρ_M, and LCV_M are the volume flow rate, density, and lower calorific value of Methanol, v_M is found experimentally for each speed, and v_L, ρ_L, LCV_L, and x_L are the volume flow rate, density, lower calorific value, and energy fraction of LPG respectively.

Conversion of volumetric emissions to specific emissions

The exhaust gas analyzer provides output in parts per million (ppm) for HC and NO_x and % of volume for CO and CO_2, which is converted to g/kWh by Eq 3.2 on a dry basis (Ağbulut et al. 2019).

$$SE_i = VE_i \left\{\frac{M_i}{M_{ex}} \times \frac{\dot{m}_{ex}}{BP}\right\} \qquad \text{Eq. 3.2}$$

$$\dot{m}_{ex} = mass\ flow\ rate\ of\ exhaust = \dot{m}_f + \dot{m}_{air} \qquad \text{Eq. 3.3}$$

M_{ex} = Molecular weight of exhaust, calculated on stoichiometric combustion
SE_i = Specific emission of any entity
VE_i = Emission data recorded by the analyzer of the entity
M_i = Molecular weight of entity

The LabVIEW-based program has been configured to sample 100 cycles, and the software uses the average data for calculation. However, the emission readings are determined on a time basis, as the exhaust gas analyzer starts reading the sample continuously, as one reading per second. Consequently, each experiment requires a minimum of two minutes of readings. For comparison and analysis, the average of the data collection is evaluated.

3.4 Details of Ammonia/Hydrogen engine test setup

Experiments are conducted on a modified 661cc single-cylinder, four-stroke, water-cooled SI engine. The cylinder block is modified to lift the combustion chamber vertically to adjust the compression ratio. A hydraulic arrangement is given, and a bolt and nut system is attached to allow lifting while the engine operates. A modified cylinder head is installed in place of the original one. It contains a spark plug and a pressure transducer (PCB Piezotronics, Model SM111A22). A throttle body assembly with manifold air pressure (MAP) sensor replaces the intake manifold. While the exhaust manifold is replaced with an exhaust line paired with a calorimeter, and a K-type thermocouple is installed 180mm from the exhaust manifold. A battery-powered capacitive discharge ignition (CDI) system is implemented. A modified flywheel with spur gear cut on one end is installed on the crankshaft and attached to the starter motor.

In addition, the crankshaft is attached for loading to an eddy-current dynamometer (Make-Technomech, Model- TMEC10). This dynamometer is equipped with a Make-Sensotronics Sanmar Ltd. model 60001 S-beam strain gauge. With the aid of a spur-gear type precision disc with a trigger mark and an optical crank position sensor (Make-Kubler, Model 8KIS40.1361.0360, Photoelectric cell), crank angles are measured. The arrangement of eight K-type thermocouples is indicated in Figure 3.3 of the schematic diagram. The panel box contains an airbox with an attached airflow transmitter (Make WIKA, Model SL-1-A-MQA-ND-ZA4Z-ZZZ), a 16-bit DAQ (NI-USB-6210), a glass-type fuel burette, a water-filled U-tube manometer, and two rotameters (Make Eureka, Model PG 5 Range 25-250 liters per hour (lph) for calorimeter, and Model A throttle control knob, ignition switch, load, speed, cooling water on/off switch, and temperature indicators are also installed. A LabVIEW-based application is employed for the analytical and graphical examination of the sensor data collected by DAQ. An ECU (Make-Performance Electronics Model PE3S) that is fully programmable regulates ignition duration, ignition angle, and spark timing. A five-gas analyzer (Indus Scientific

Pvt. Ltd., Model-PEA205) measures CO (%), CO_2 (%), O_2 (%), unburned HC (ppm), and NOx in exhaust emissions (ppm).

Hydrogen and ammonia have separate channels in the fuel supply line. The hydrogen gas is supplied by a 150bar hydrogen cylinder linked to a water-filled flame trap and an H_2 rotameter (Make- Tansa Equipment, HS-90261090, 0-200 lpm, least count 0.1 lpm). Similarly, ammonia is delivered from a 9 bar ammonia cylinder. In addition, the ammonia cylinder's supply valve is coupled to a rotameter (Make- Tansa Equipment, 0-5 kg/hr, minimum count 0.2 kg/hr). Before the mixing chamber, the hydrogen and ammonia lines are equipped with a non-return valve. The blended fuel is fed from the mixing chamber to an electronically controlled fuel injector (Make: Stag, Model: AC-W03). Both fuels are delivered at a pressure of 1.2 bar, and rotameter-equipped valves control the flow rate. The sensors and DAQ are mentioned in Table 3.2, and the technical specifications of the gas analyzer are in Table 3.3.

Table 3.2. Sensors and measuring units Specifications.

Dynamometer	Eddy-current type, water-cooled (Make-Technomech, Model-TMEC10)
ECU	PE3 Series ECU, Model PE3-8400P
Piezo sensor	PCB Piezotronics, Model SM111A22
Crank encoder	Make Kubler, Model 8. KIS40.1361.0360, Resolution 1 Deg, Speed 5500 rpm with TDC pulse
Gas ECU	Stag AC300
Gas Injector	Stag IG 01, single hole, 0.5-2.5 bar
Gas flowmeter	Make- Tansa Equipment, HS-90261090, 0-200 LPM, least count 0.1 lpm
DAQ	16-bit, 250kS/s, NI-USB-6210
Load Sensor	Make Sensotronics Sanmar Ltd., Model 60001, type S beam, Universal, Capacity 0-50 kg.
Air Flowmeter	Make WIKA, Model SL-1-A-MQA-ND-ZA4Z-ZZZ, output 4-20 mA, supply 10-30 Vdc, conn. 1/2"NPT (M), Range (-)25 - 0 mbar

Water rotameters	Make Eureka Model PG 5 & PG 6, Range 25-250 lph/40-400 lph, Connection ¾" BSP vertical, screwed, packing neoprene.
Temperature sensors	Type RTD, PT100: - 1 K-type thermocouple: - 8

Table 3.3 Gas analyzer technical specification

Measured parameter	**Measuring Range**	**Accuracy**
Carbon monoxide	0-10% vol	<0.6% vol: ±0.03% vol >0.6% vol: ±5% vol
Hydrocarbon	0-20000 ppm	<200ppm: ± 10ppm >200ppm: ± 5% of ind. value
Carbon dioxide	0-20% vol	<10% vol: ±0.5% vol >10% vol: ±5% vol
Nitrogen oxide	0-5000 ppm	<500ppm: ± 50ppm
Oxygen	0-22% vol	<2%vol: ±0.1% vol >2% vol: ±5% vol

Figure 3.3 Experimental Lab Setup

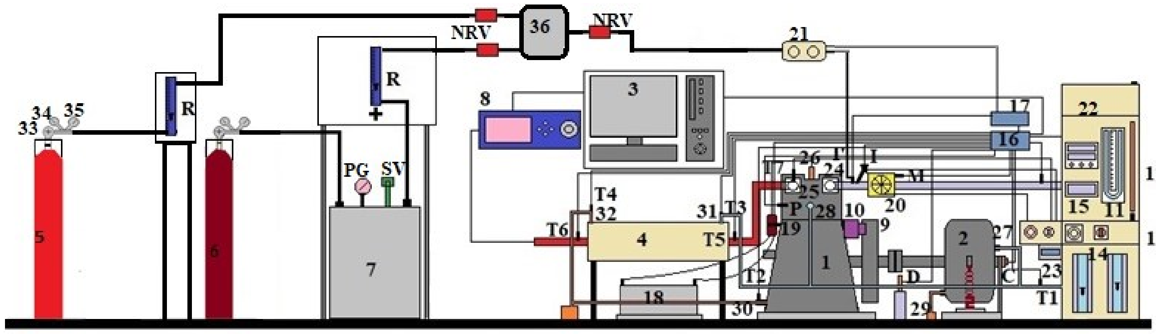


Figure 3.4 Schematic of the test setup (Ammonia/Hydrogen)

1-Engine, 2-Dynamometer, 3-Computer, 4-Calorimeter, 5-Ammonia cylinder, 6-Hydrogen cylinder, 7-Wet flame arrester, 8-Exhaust gas analyzer, 9-Flywheel, 10-Starter motor, 11-Manometer,12-Fuel burette, 13-Air-box, 14-Water rotameters, 15-Load knob, 16-Open ECU (main), 17-Gas ECU, 18-Battery, 19-Capacitor, 20-Throttle-body, 21-Sequential reducer, 22-Fuel tank, 23-T7 display, 24-Inlet-manifold, 25-Exhaust manifold, 26-Spark-plug, 27-Water inlet (dynamometer), 28-Water inlet (engine), 29-Water outlet (dynamometer), 30-Water outlet (engine), 31-Water inlet (calorimeter), 32-Water outlet (calorimeter), 33-Control Valve, 34-Line Pressure Gauge, 35-Delivery Pressure Gauge,36-NH_3 & H_2 mixing chamber, PG-Pressure Gauge, R-Gas rotameter, SV-Safety valve, NRV-Non returning valve, M-MAP Sensor, C-Crank position sensor, P-Pressure transducer, T1-Thermocouple (inlet water, engine & dynamometer), T2-Thermocouple (outlet water engine), T3-Thermocouple (inlet water, calorimeter), T4-Thermocouple (outlet water calorimeter), T5-Thermocouple (exhaust gas inlet calorimeter),T6-Thermocouple (exhaust gas outlet calorimeter),T7- Thermocouple (exhaust gas, manifold)

3.5 Methodology for the Ammonia/Hydrogen experimental investigation

3.5.1 Plan and procedure

The experimental study will be conducted in three stages based on the objectives and goals shown in the flow chart. In the first stage, variable CR and hydrogen energy fractions are studied, variable ignition timing and CR are studied in the second stage, and the third stage focuses on EGR. Two engine speeds, 1400 rpm and 1800 rpm, were used for all of the tests conducted under WOT conditions. The first stage of the studies in ammonia/hydrogen was planned in two phases, targeting the objectives simultaneously; in the first phase, variable CR was explored using varied blending ratios while the ignition was held constant. Figure 3.5 depicts the experimental scheme flowchart. The CR ranges from 12 to 15, and the hydrogen energy fraction varies between 5% to 21%. Here, the tests are designed for beginning at CR12, where the hydrogen energy percentage will be altered from 5% to 21%; once the CR12 studies are complete, the engine is adjusted to achieve CR13, and the same procedure is utilized. Likewise, experiments are undertaken in order to achieve the aims. After comparing the results, a set of optimal CR and hydrogen energy fractions is determined by a trade-off between BTE. In the second phase, at the optimal hydrogen energy fraction, both ignition timing and CR are varied; in this case, CR is altered between 14 and 16. The ignition timing study scope ranges from 18 ºCA bTDC to 32 ºCA bTDC. Experiments are planned to be conducted at a fixed hydrogen energy percentage while IT is adjusted; once the experiments are complete, the subsequent CR is determined. The next step of experimentation is established by comparing data and analyzing the effects, and the optimal condition is chosen. The third phase of the experiment focuses on the following objectives. Here, second-phase NOx emissions are studied for NOx management via EGR. The EGR is varied from 5% to 20% at a rate of 2.5 percentage points.

Investigations are conducted under wide-open throttle conditions for two speeds, 1400 rpm & 1800 rpm, and the spark timing is fixed at 24ºCA bTDC. The CR is varied from 12 to 15. On the other hand, hydrogen blending in ammonia is achieved based on energy fraction. Five energy fractions of hydrogen, 5%, 9%, 13%, 17%, and 21%, are used at each CR. The injection pressure of the blend is maintained at 1.2 bar. Since ammonia has a low heating value and stoichiometric air requirement, the injection duration is kept maximumly allowable by the ECU, which is 12mS, corresponding to the total inlet valve opening duration at 1800 rpm. For each set of experiments, 100 cycles are sampled, which is used to analyze by a LabVIEW-based program. After achieving the optimal hydrogen fraction in the second stage, we did similar experiments based on variable ignition timings. All tests are performed with a wide throttle, at speeds between 1400 rpm and 1800 rpm, and with ignition timing ranging from 32 ºCA bTDC from 18 ºCA bTDC. CR varies between 14 and 16. In contrast, an energy portion is used to complete the hydrogen addition to ammonia.

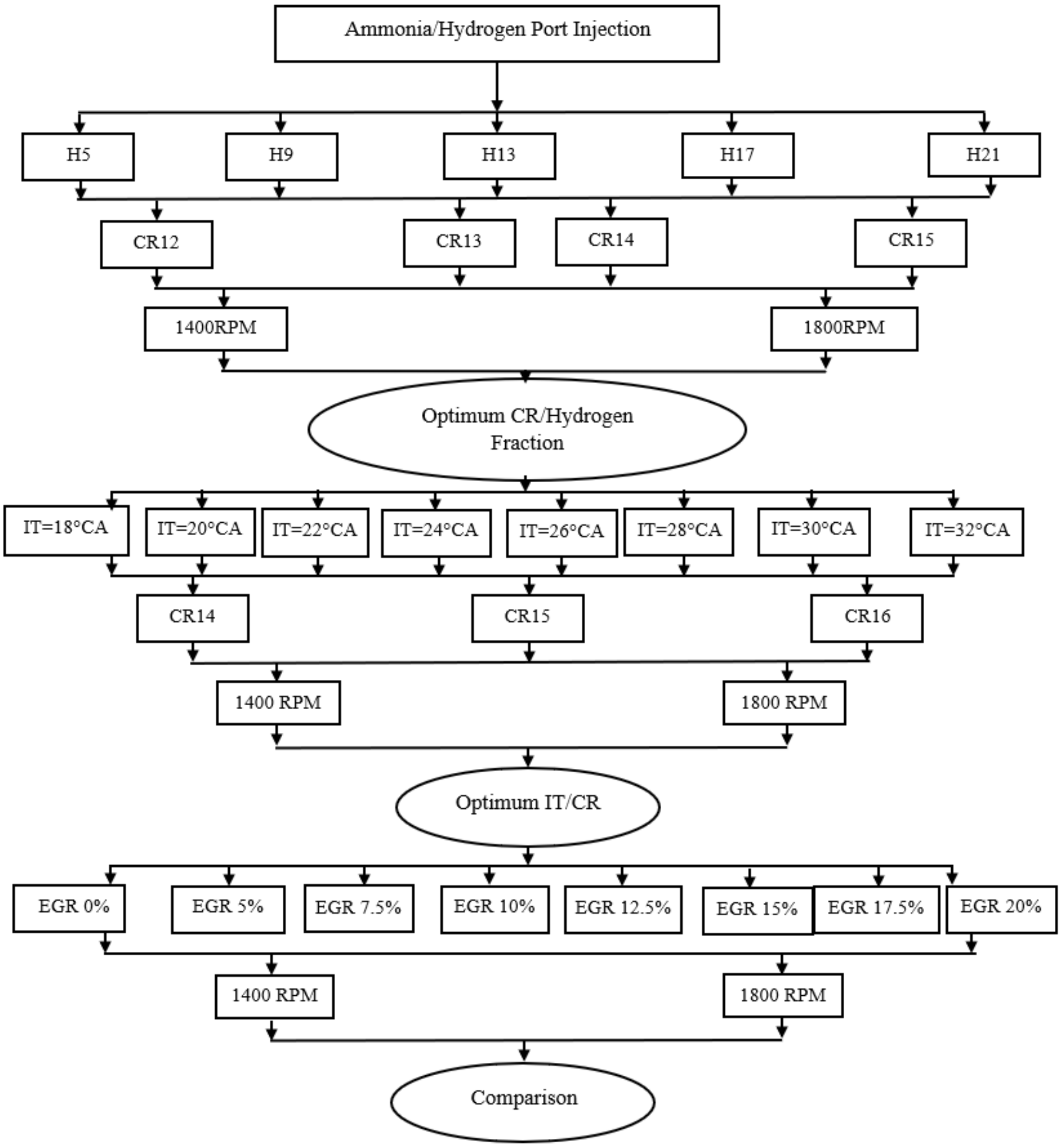


Figure 3.5 Experimental scheme

Each CR makes use of 21% hydrogen energy fractions. Though the modification of the cylinder block to raise the combustion chamber vertically is one method for adjusting the compression ratio without altering the combustion geometry. Within the specified range, the CR can be adjusted without stopping the engine; however, after each series of trials, the engine is stopped and allowed to restore to near-initial conditions. At all times, the injection pressure of the mixture is maintained at 1.2 bar. Due to the extremely low heating value and stoichiometric air need for ammonia, the ECU limits the injection duration to 12mS, which corresponds to the duration of the inlet valve opening at 1800 rpm. Each experiment is conducted twice to reduce the possibility of error. One hundred cycles are collected for each set of trials, and the average is calculated using a LabVIEW-based application.

3.5.2 Calculations

Hydrogen flow rate calculation

The global stoichiometric reaction of NH_3/H_2/air combustion is as:

$$\left(1-x_{H_2}\right)NH_3 + x_{H_2}H_2 + \frac{3-x_{H_2}}{4}\left(O_2 + 3.76N_2\right) \rightarrow \left(\frac{3-x_{H_2}}{4}\right)H_2O + \left(\frac{1-x_{H_2}}{2} + 3.76 + \frac{3-x_{H_2}}{4}\right)N_2 \qquad \text{Eq. 3.4}$$

Here, the molar fraction of hydrogen x_{H_2} is found through the energy fraction $\bar{x}_{H_2}$ by equation 3.5,

$$x_{H_2} = \frac{\left(\bar{x}_{H_2} \times E\right)}{lcv_{H_2} \times M_{H_2}} \qquad \text{Eq. 3.5}$$

Here, E is the total fuel energy supplied in kJ, lcv_{H_2} is the lower calorific value of hydrogen in kJ/kg, and M_{H_2} is the molecular weight of hydrogen in kg/mol.

3.6 Modification in the test setup

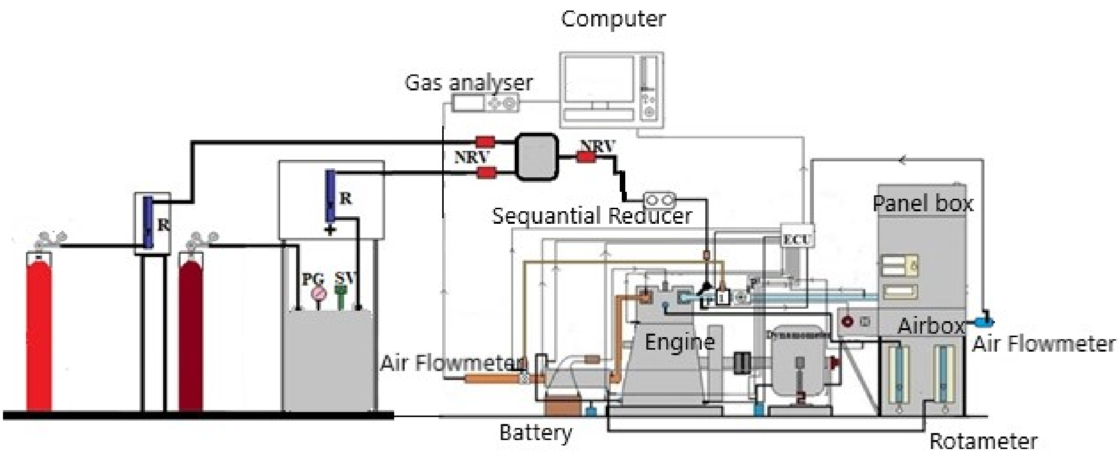


Figure 3.5. Experimental Test Rig with EGR arrangement (Ammonia/Hydrogen)

The experimental setup is slightly modified for stage 2 experiments, in which a manually operated EGR system is attached, as shown in the Figure 3.5. The EGR system involves an insulated EGR supply line made up of mild steel and covered by glass wool. After the exhaust cooler, a T section is installed in the exhaust section to house the ball valve working as an EGR valve. A T-type exhaust gas mixing section is attached to the intake line between ammonia/hydrogen port injection, and the throttle body connects the EGR line. Another air flowmeter is installed at the EGR valve to measure EGR mass flow rates. The air supply box is connected to the dial-type pressure gauge.

3.6.1 Calculation of EGR rate

The EGR flow rate can be determined by using the mass of fresh air, EGR, and the mass of fuel. Here, information is gathered from the two differential pressure sensors, which provide output in millimetres of the water column.

Eq.3.6 is used to calculate the EGR ratio;

$$EGR\ \% = {\dot{m}_{EGR}}\Big/{(\dot{m}_{EGR} + \dot{m}_{exhaust})} \qquad \text{Eq. 3.6}$$

Here,

$$\dot{m}_{exhaust} = \dot{m}_{air} + (\dot{m}_{H_2} + \dot{m}_{NH_3}) \qquad \text{Eq. 3.7}$$

Here, $\dot{m}_{EGR}$ is EGR mass flow rate (g/s), $\dot{m}_{exhaust}$ is exhaust mass flow rate (g/s), $\dot{m}_{air}$ is intake air mass flow rate, $\dot{m}_{NH_3}$ is ammonia mass flow rate (g/s)and $\dot{m}_{H_2}$ is hydrogen mass flow rate (g/s).

$\dot{m}_{EGR}$ and $\dot{m}_{air}$ are computed from the differential air pressure sensor using Eq.3.8, assuming that the exhaust gas is air.

$$\dot{m}_{air} = \sqrt{(2g \times \rho_{air} \times \rho_{water} \times h_{water})} \times A_m \times C_d/10^3 \qquad \text{Eq. 3.8}$$

Here, g is the acceleration due to gravity (m/s^2), ρ_{air} is the density of the air (kg/m^3), ρ_{water} is the density of water (kg/m^3), h_{water} is the differential pressure reading of the air pressure sensor in mm of the water column, A_m is orifice area (3.142×10^{-4} m^2 for both airbox and EGR throat), and C_d is coefficient of discharge (0.6 for both airbox and EGR throat).

During EGR control, an excel program is utilized to feed the sensor output; the control valve position is adjusted based on the EGR rate needed.

3.7 Uncertainty Analysis

Evaluation of experimental uncertainty and error is necessary to assure the validity of the completed research. Numerous sources of uncertainty include weather, equipment selection, calibration, observation, and inaccurate reading. Using the approach of partial differentiation, the uncertainty percentages of different measurement instruments are used to examine dependent variables such as BTE and brake power.

Experiments are performed to determine the mean values of parameters ($\bar{\bar{x}}$) and the standard deviation (σ_i) of any measured parameter (x_i) for a certain number of measurements. Calculating the mean, standard deviation, and standard error for the repeated 20 measurements yielded uncertainties for the independent variables.

$$W_i = \frac{2\sigma}{X} \times 100 \qquad \text{Eq. 3.9}$$

The overall uncertainty is examined as follows:

$$= \sqrt{}\{(NO_X)^2 + (speed)^2 + (time)^2 + (BP)^2 + (BTE)^2 + (cylinder\,pressure)^2 + (crank\ angle)^2 + (manometer)^2\} \qquad \text{Eq. 3.10}$$

The uncertainty analysis is performed for instrumental variables like speed, load, and dependent variables like brake power (BP) and efficiencies, using Eq.3.10. The overall uncertainty calculated was found here, ± 2%.

CHAPTER 4

RESULTS AND DISCUSSION

The experiments are performed under WOT conditions for five speeds in methanol/LPG (1400 rpm-1800 rpm) and two speeds in ammonia/hydrogen (1400 rpm and 1800 rpm). To prevent pre ignition, the CR of gasoline is set to 11 and the IT is maintained at 24 ºCA bTDC. This CR and IT refers to the BTE maximum for gasoline. The results for methanol/LPG and ammonia/hydrogen fuelling are categorized by speed and compared to the optimal gasoline results. Since the study aims to examine the impacts of CR, LPG fractions, hydrogen energy fractions, IT, and EGR, graphs against these parameters are created. However, the outcomes are compared by the experimental design.

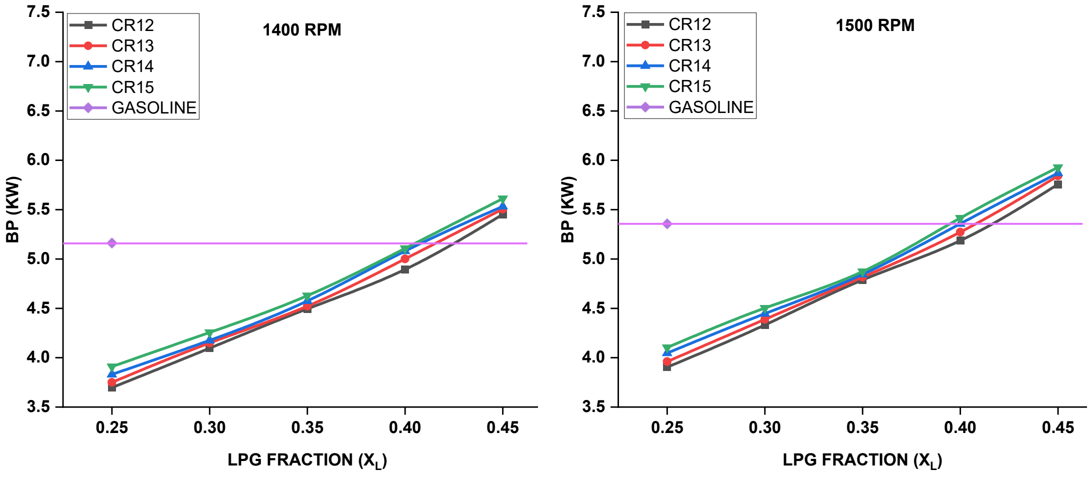
Consequently, plausible explanations are discussed next; in this section, the first section discusses the effects of CR and LPG fraction on methanol/LPG fuelling, and the second section discusses the effects of CR and hydrogen energy fraction on ammonia/hydrogen fuelling. The third section discusses the effects of IT and CR on ammonia/hydrogen fuelling. The final section explains the combined strategy of EGR (ammonia/hydrogen).

4.1 Influence of CR and blending ratio (Methanol/LPG)

Experiments are conducted with the utmost care, since engines are cooled after each experiment and compression ratios are altered under cold engine conditions. All sorts of equipment are thoroughly inspected, and the outcomes of the two repetitions are also tallied. Regularly, after each set of experiments, the data are analysed, and comparative research is conducted and summarised as follows:

4.1.1 Brake power

As methanol has a lower volumetric energy density than gasoline, achieving equivalent BP to gasoline is challenging. Methanol/LPG, on the other hand, have a faster flame speed than gasoline, resulting in a more significant mass fraction being burned and, consequently, a larger work output each cycle that overcomes limits. The change in BP production of methanol/LPG mixtures with varied CR, speed, and LPG fractions is depicted in Figure 4.1. With a CR of 11 gasoline has a maximum power output of 5.82kW at 1800 rpm, whereas methanol/LPG fuel has a maximum power output of 6.87kW at 15CR. It has been determined that methanol/LPG fuel provides 18.0% more engine power than gasoline. Figure 4.1 shows that brake power increases linearly with speed; however, it is also observed that the increasing LPG energy fraction has raised the BP since the overall energy added to the system increases (Raviteja and Kumar 2015). Increasing CR is found to increase BP at all LPG fractions; additionally, CR's effect is identical at all speeds and for nearly all LPG fractions. Boosting CR is responsible for increasing the cylinder pressure at the time of ignition and, consequently, the cylinder temperature, which removes any latent loss and creates a condition appropriate for rapid combustion (Hotta et al. 2020). At a low LPG fraction, WOT conditions produce a lean mixture, which requires a relatively high pressure to compensate for the latent losses due to methanol. However, increasing the CR has a significant effect on BP, whereas, at a high LPG fraction, the relatively rich mixture burns smoothly, and a further increase in the CR has no effect to that extent (Duan et al. 2019a). Compared to the speed at any fixed LPG energy fraction and CR, increasing the speed from 1400 rpm to 1800 rpm results in an average 22% increase in BP. The probable cause is that increasing speed leads to an increase in the number of cycles per unit time, increasing work output per unit time and, consequently, the BP (Heywood 1988).



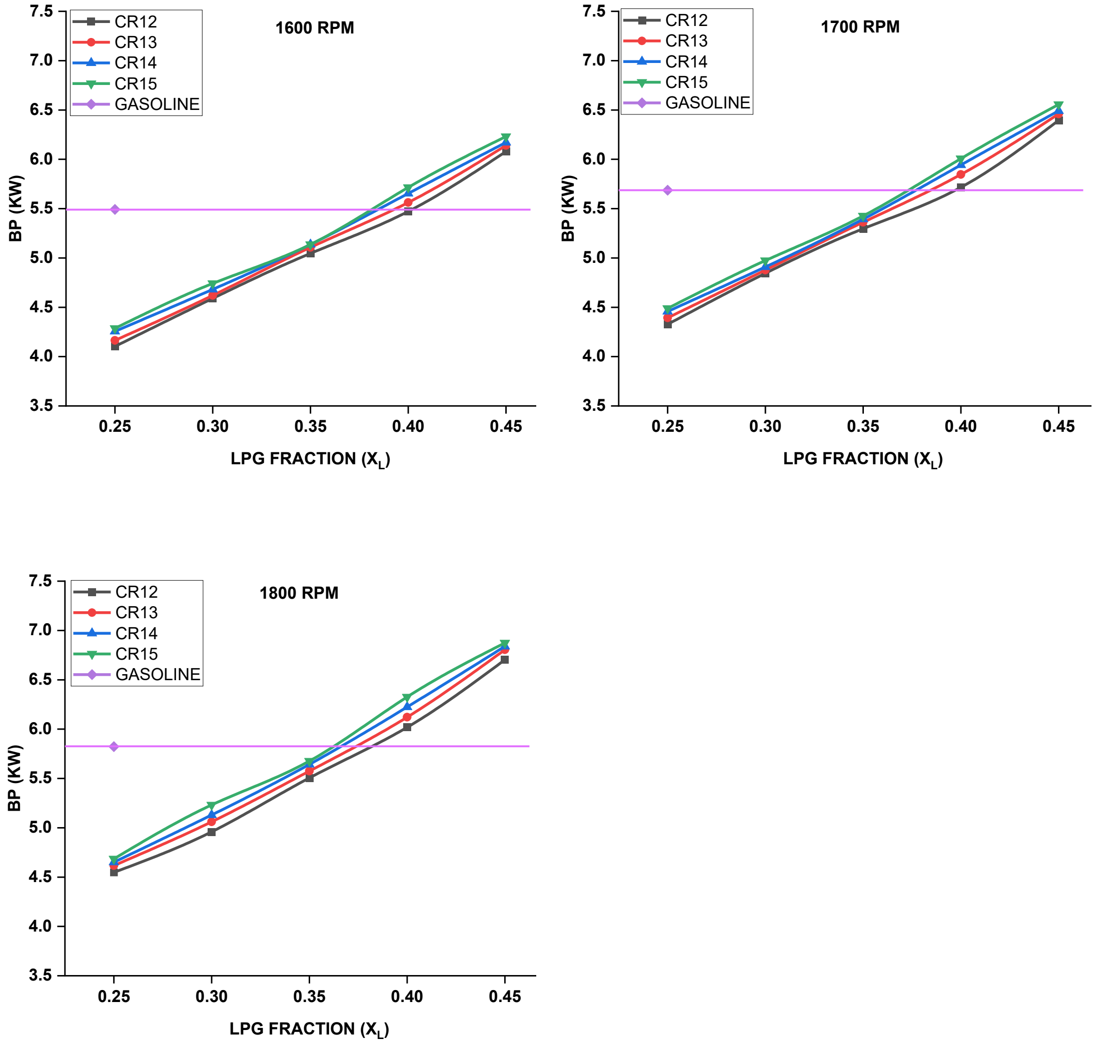
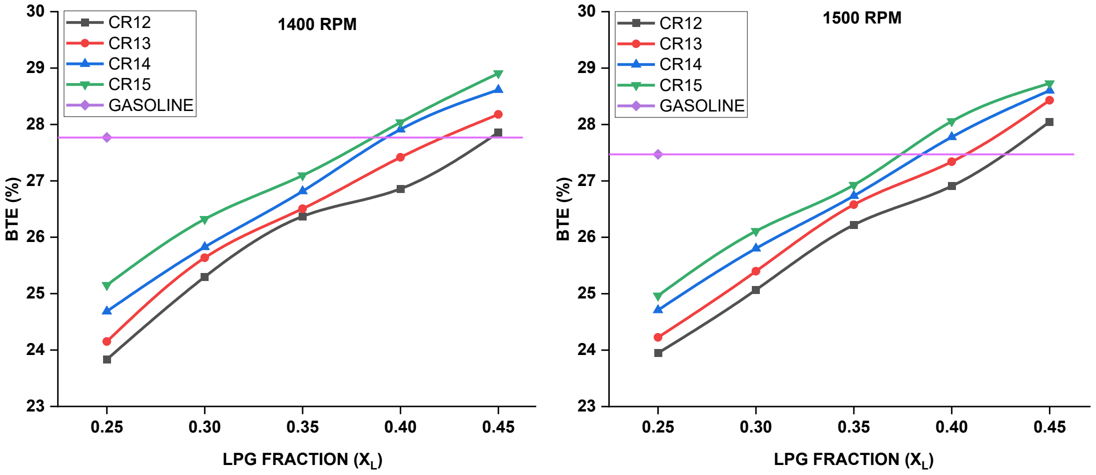


Figure 4.1 Brake Power variations with LPG fractions and CR at different speeds

4.1.2 Brake thermal efficiency

It has been observed that methanol/LPG fuel has a higher BTE than gasoline. Maximum efficiency of 28.906% was achieved at 15CR at 1400 rpm and 20°CA bTDC ignition timing. Higher oxygen in methanol permits the available percentage of fuel to mix with oxygen to provide high combustion efficiency. For any speed and CR, Figure 4.2 shows that the BTE continues to rise when the LPG fraction is increased. Increment per 5% blend ratio is more noticeable at low speeds than at high speeds, as at 1400 rpm, an average change of 5% is observed at CR12, but at 1800 rpm, this average change is reduced to 3.9% at the same CR. At 1400 rpm and 25% LPG fraction, BTE increases by an average of 5.5% every CR, whereas it decreases by 3% at the same speed as the

45% LPG fraction. As speed increases, the increase in BTE per CR decreases as well. Increasing CR has a favorable effect on BTE because it minimizes pumping loss. It also increases air intake, particularly at high speeds when the increased number of cycles per unit time prevents the engine from cooling down and releasing all of its exhaust gases efficiently. The high speed also increases the temperature inside the cylinder, resulting in a rise in the intake charge temperature. It decreases the bulk of the working fluid in the combustion chamber, resulting in a low work output per unit cycle and a lower BTE (Awad et al. 2018a). It is evident from the BTE graphs shown in Figure 4.2; raising the speed causes the BTE to grow up to 1600 rpm or 1700 rpm, depending on the LPG fractions, and then declines at higher speeds. As the ratio of volatile fuel to total fuel grows in the combustion chamber, the latent losses of methanol decrease, which is one of the most significant outcomes observed here (Gong et al. 2019). It improves the efficiency and speed of fuel combustion, resulting in a higher BTE. As the CR increases, the situation becomes more favorable. This increase is also caused by the removal of excess air in the combustion chamber, which creates a rich mixture, but the condition is still sufficiently lean to be termed "lean." The relatively rich mixture is now easy to ignite and promote combustion (Masi 2012).



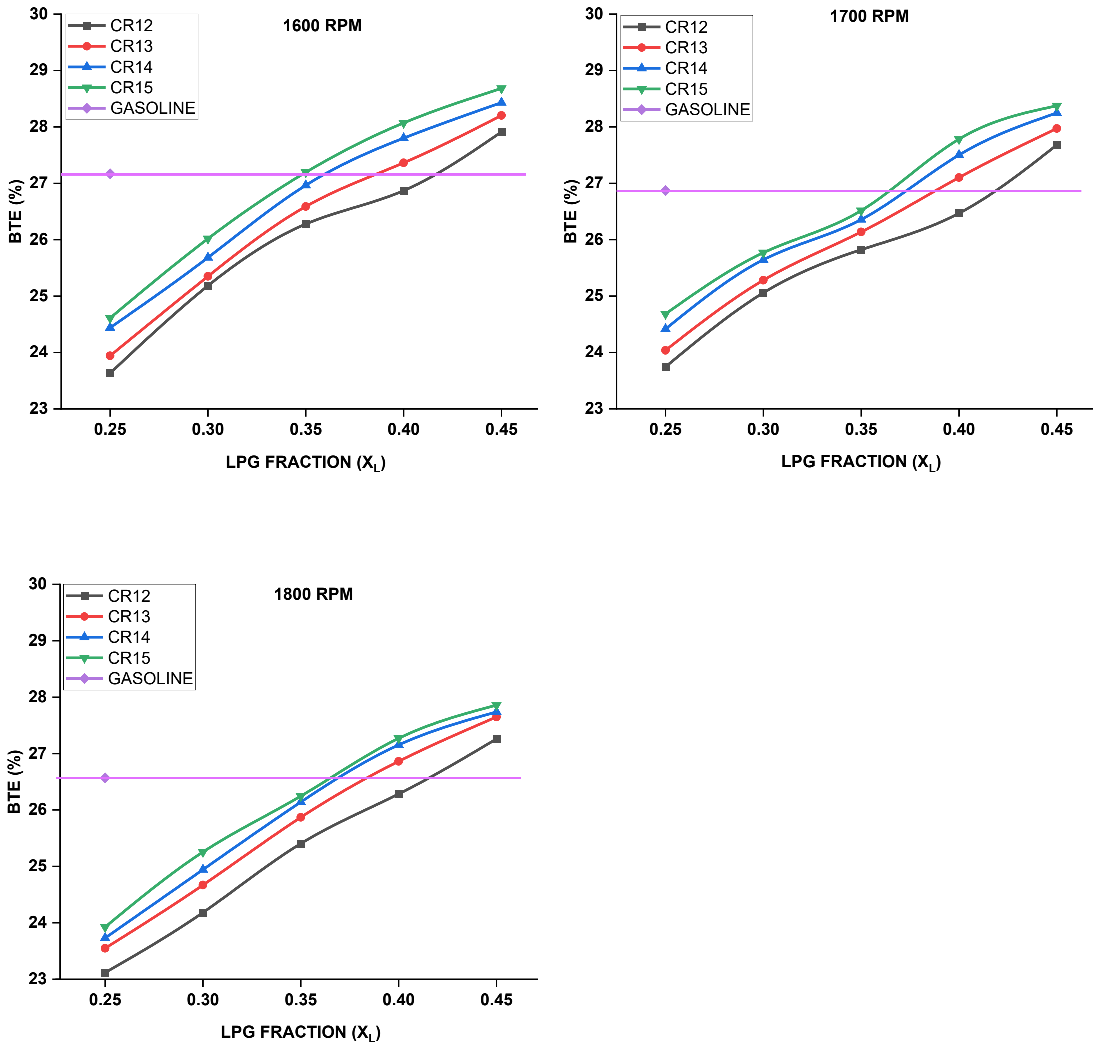
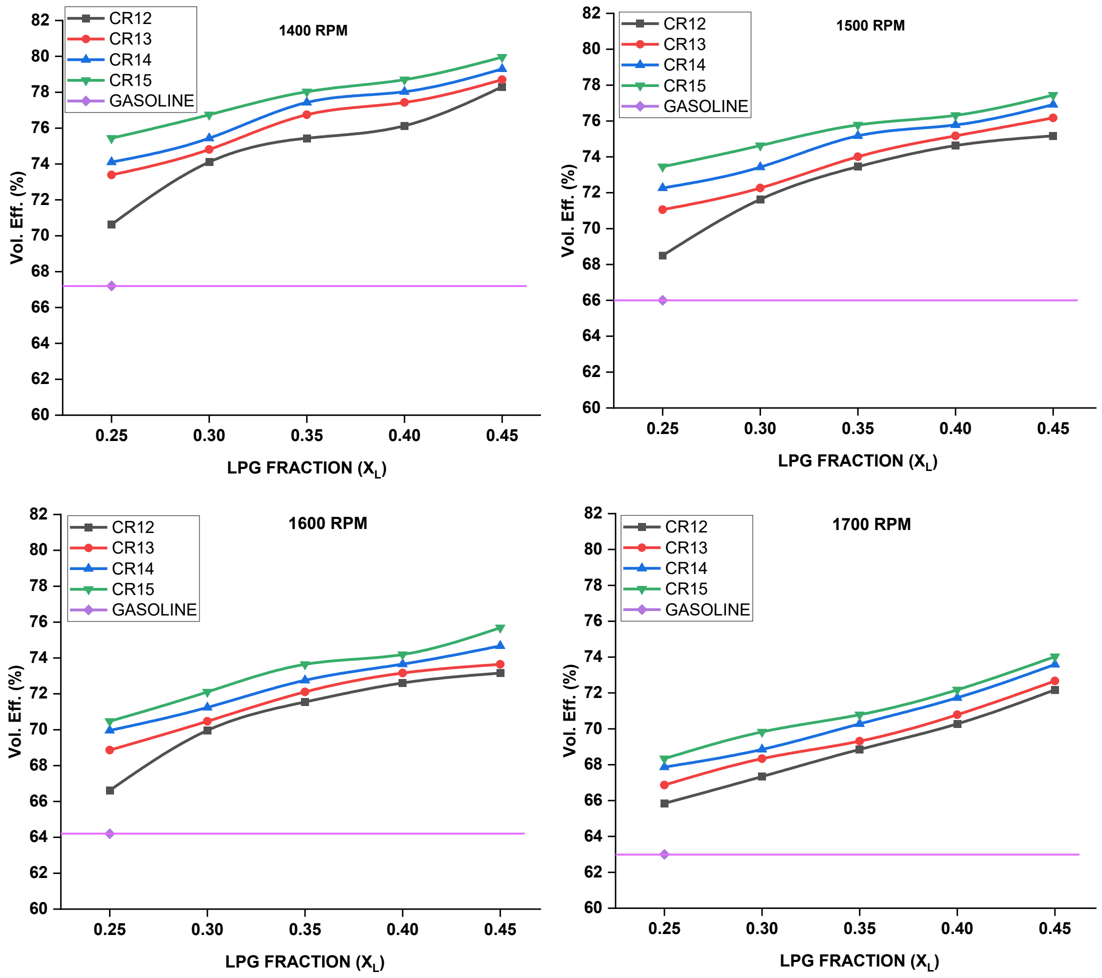


Figure 4.2 BTE variations with LPG fractions and CR at different speeds

4.1.3 Volumetric efficiency

Methanol/LPG fuel had a volumetric efficiency value of 79.95% at 15CR,1400 rpm, and a 45% LPG energy fraction at 20°CA bTDC, which was more than gasoline's value of 67.2% under identical conditions. The total increase of η_{vol} exceeds that of gasoline by 15.94%. Due to an excessively lean mixture at low speed and low LPG fraction, it is difficult to operate the methanol-fuelled engine under WOT conditions at full load (Hu et al. 2007); thus, the LPG fraction is maintained at a minimum of 25%. Figure 4.3 shows the variation in η_{vol} by speed for different LPG fractions and CRs. The increasing LPG fractions at all speeds were shown to be advantageous for η_{vol}, with the rate of increase being greater for low CRs than for high CRs. As speed increases, available time decreases, resulting in exhaust and inlet being relatively incomplete. With higher speed, the residual gas fraction (RGF) increases, resulting in a prolonged expansion, which decreases the effective suction duration and results in a reduced η_{vol} (Çinar et al. 2016; Heywood 1988; Luo et al. 2019). At high speeds, the drop in η_{vol} contributes significantly to the decrease in BTE. The increased CR decreases the clearance volume, resulting in a low RGF, which decreases the expansion time, hence causing a rise in η_{vol} (Kalra et al. 2014; Mohammed et al. 2020). Also, the LPG is probably heavier than air gas, increasing the momentum at the intake manifold and leading to an effective suction. The exhaust gases also get removed effectively during the overlap period by this colder and heavier charge getting in faster (Gumus 2011).



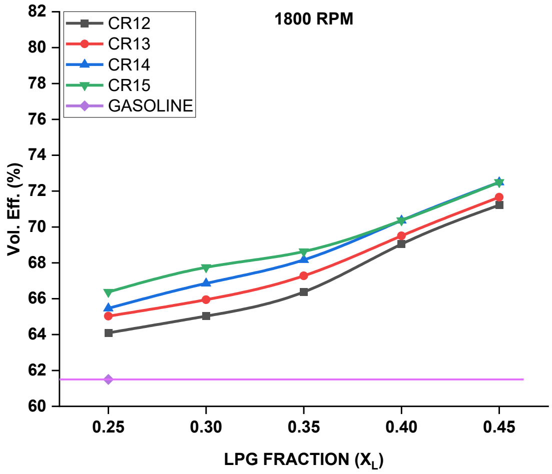


Figure 4.3 Volumetric Efficiency variations with LPG fractions and CR at different speeds

4.1.4 Maximum cylinder pressure

Maximum cylinder pressure (P_{max}) increases with increasing LPG fraction and CR, with the LPG fraction having a greater effect than CR. However, the energy given by methanol/LPG is less than that of gasoline; hence P_{max} slightly lesser, as shown in Figure 4.4. For all speed ranges P_{max} is observed to be lowest for a 25% LPG fraction, while raising CR increases P_{max}. At low speed, increasing CR has a modest rate of P_{max} increase; however, at high speed, the rate of P_{max} increase is greater. In contrast to an increase in CR, the P_{max} rate decreases with increasing LPG fraction, with the effect being less noticeable at low speed and greater at high speed. Figure 4.4 shows the differences in P_{max} regarding CR and LPG fractions at various speeds. A 25% LPG fraction is found to have the lowest P_{max} under all conditions. For 25% LPG, there is an average of 7.8% higher in P_{max} per CR at 1400 rpm, which decreases to 6% per CR at 1800 rpm. Increasing LPG fraction increases the P_{max} rate; for 45% at 1400 rpm, the average increase is 14% per CR, which decreases to 11.8% per CR at 1800 rpm. Over the whole CR, the average increase in P_{max} every 5% LPG fraction ranges from 13% at 1400 rpm to 10% at 1800 rpm. Increasing CR increases the amount of pressure at the ignition timing, and as temperature decreases the delay period and higher pressure before ignition, P_{max} is expected to increase as well (Duan et al. 2019b; Movileanu et al. 2020). On the other hand, the increasing LPG fraction decreases the amount of extra air, which

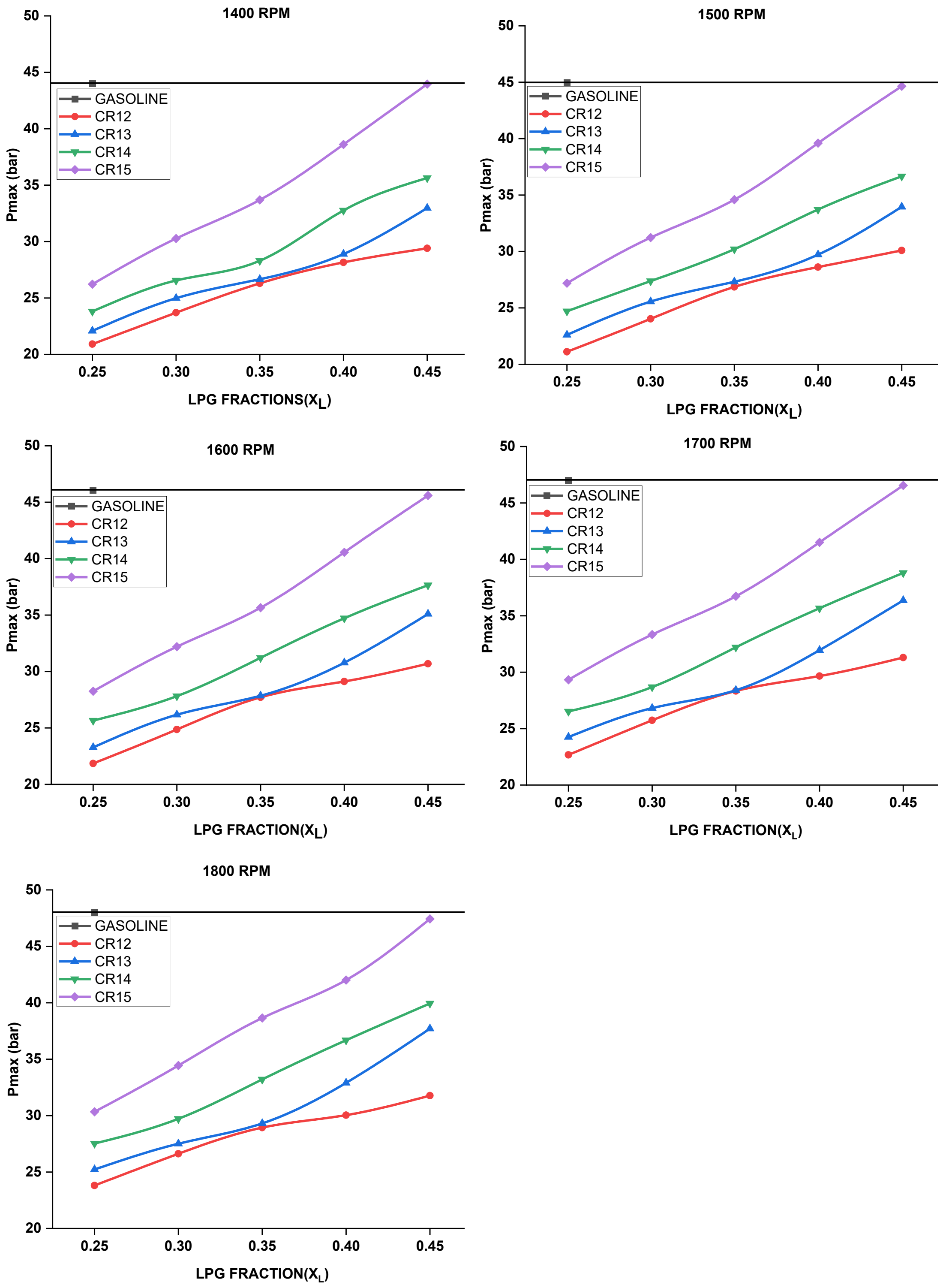
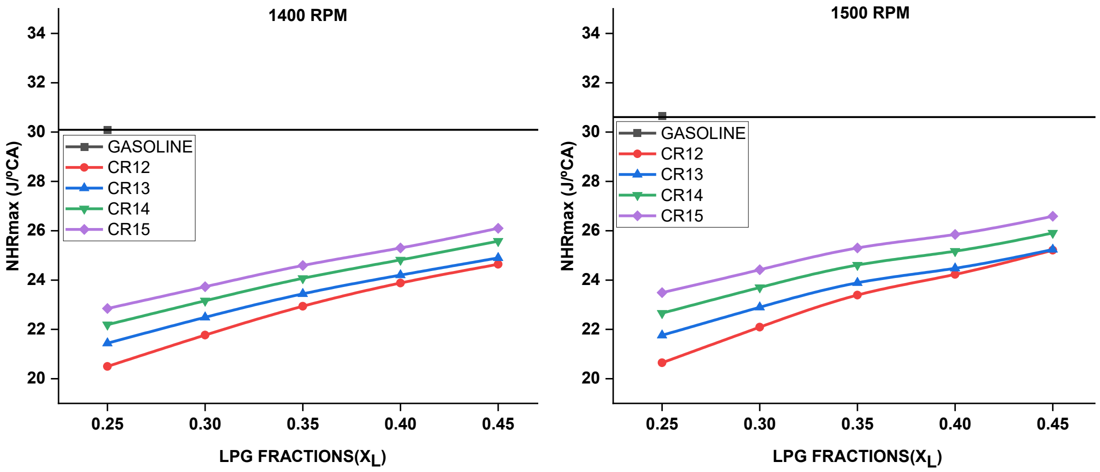


Figure 4.4 Maximum cylinder pressure variations with LPG fractions and CR at different speeds

promote the charge to burn in a relatively rich atmosphere and, along with the increased energy added to the system, increases the P_{max} (Calam 2020). The increasing speed causes the cylinder wall temperature to rise, resulting in the quick heating of the incoming charge and relatively high pressure at the time of ignition, leading to a higher P_{max} (Nuthan Prasad et al. 2020a).

4.1.5 maximum net heat release rate

Figure 4.5 shows the NHR_{max} changes. Even when methanol is blended with LPG, the higher latent heat of vaporization, lower heating value, and higher autoignition temperature reduces the heat release rate comparable to gasoline. Figure 4.5 shows that the NHR_{max} follows the same trend as P_{max} fluctuations. The rate of rise in NHR_{max} is shown to be proportional to speed. For low speeds of 1400 rpm and 1500 rpm, the rate of increase in NHR_{max} drops rapidly until the LPG fraction reaches 35%, then slowly afterward. For speeds greater than 1500 rpm, the rate of increase in NHR_{max} decreases to 40% LPG and then increases slightly for 45% LPG. However, at 1800 rpm, the rate of increase in NHR_{max} increases with increasing LPG fraction. The increasing CR is found to be responsible for increasing the cylinder pressure and temperature at ignition, leading to increased tumble moment and homogeneity, as well as decreasing the ignition delay, resulting in a shorter flame development duration, as well as the flame propagation, resulting in NHR_{max} and faster combustion (Duan et al. 2019a; Gong et al. 2016; Sakthivel et al. 2020a) (Hotta et al. 2020).



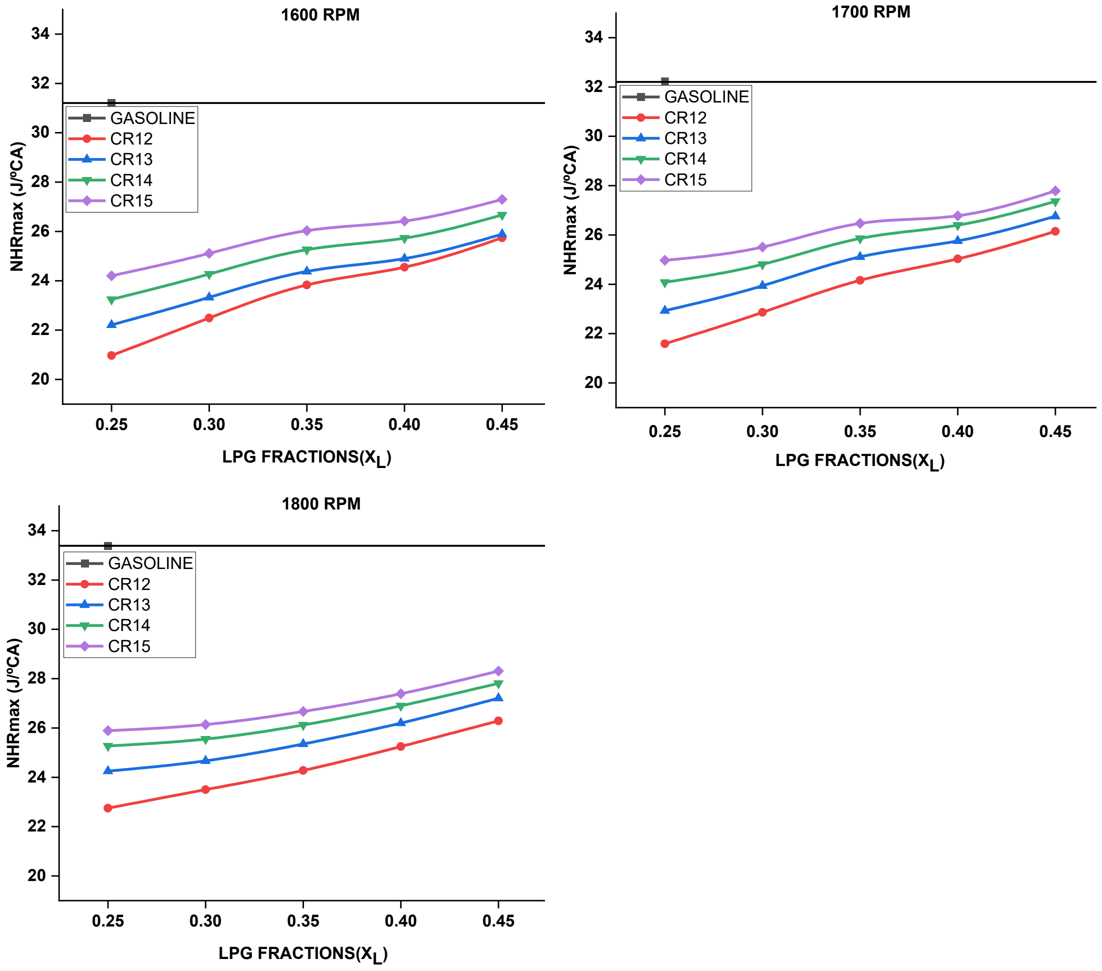


Figure 4.5 Maximum NHR_{max} variations with LPG fractions and CR at different speeds

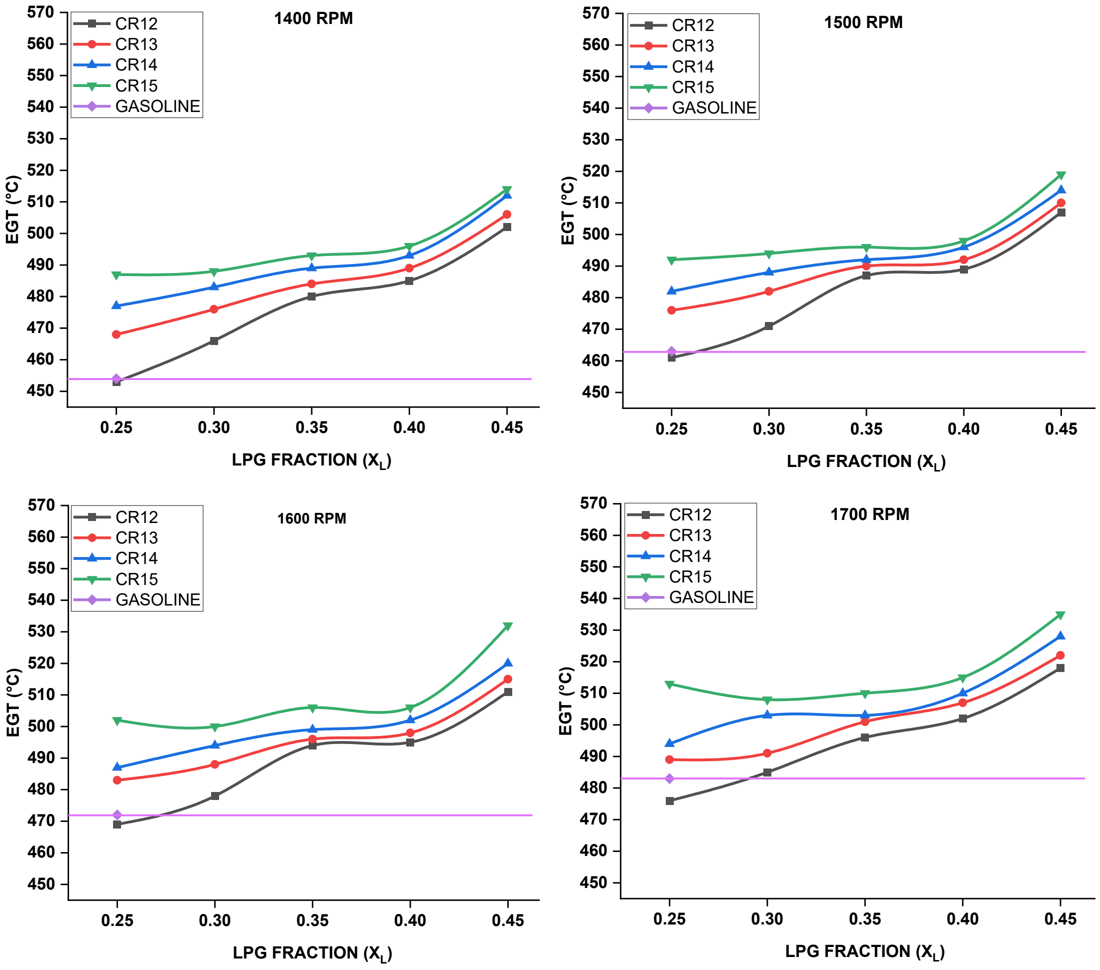
On the other hand, the increasing LPG proportion increases both the net heat delivered to the system and the amount of highly volatile fuel, resulting in an increase in the heat release rate; however, the accumulation of LPG results in a slightly longer combustion duration.

4.1.6 Emission characteristics

Exhaust gas temperature

Figure 4.6 shows that EGT increases with increasing speed, LPG fraction, and CR. At a constant speed, it is observed that increasing CR increases the EGT, but the effect is greater at low LPG fractions than at higher LPG fractions, as the rate of increase in EGT at 1400 rpm changes from 3.31% per CR to 2.09% per CR for 25% LPG, while it decreases from 0.79% per CR to 0.39% per CR for the same CR change at 45% LPG.

However, increasing speed decreases this rate of increase by up to 35% at low LPG fractions and increases it at high LPG fractions. Similarly, the influence of LPG fractions on EGT is more noticeable at low speed and low CR than at high speed and high CR. At 1400 rpm and CR12, there is an average change of 2.2% in EGT per 5% LPG fraction, which decreases to 0.8% at 1800 rpm. However, LPG concentrations of more than 35% have the reverse effect, as the rate of temperature rise increases significantly. Increasing CR results in increased thermal properties of the combustion chamber and working fluid, resulting in an increased mean temperature, which results in high EGT (Yousufuddin and Masood 2009), which at low speed, and increasing LPG fractions results extensively as a result of an increase in heat addition. While increasing the speed, the mean gas temperature also rises (Ozcan and Yamin 2008), which is compounded by increases in LPG fractions; under these circumstances, increasing CR has a minimal influence on EGT (Javaheri et al. 2014).



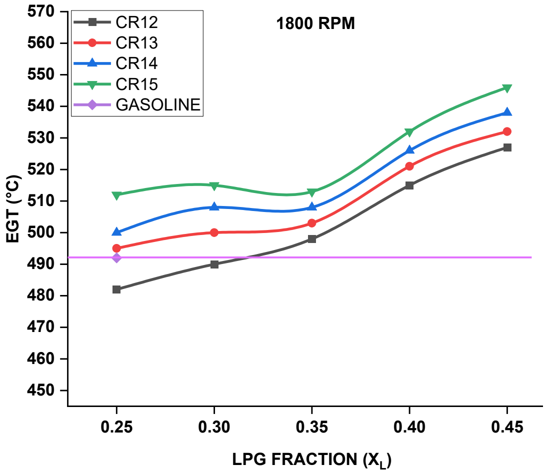


Figure 4.6 Exhaust gas temperature variations with LPG fractions and CR at different speeds

In addition, the high LPG percentage causes an increase in the late burning period due to the quickly decreasing cylinder pressure at a relatively high speed, resulting in an increase in EGT (Yücesu et al. 2006). Due to the late burning of methanol, the EGT is higher than gasoline.

Carbon monoxide emission

CO emission indicates incomplete combustion or disassociation reaction (Heywood 1988); however, in the case of low LPG fraction and low speed, the potential of disassociation reaction is negligible; therefore, incomplete combustion is the governing factor. As speed increases, the probability of dissociation reaction shifts. As seen in Figure 4.7, the CO emissions increase as the speed increases under all conditions. Similar to the increase in CO emissions with increasing LPG fraction, the increase in CO emissions with increasing LPG fraction at low speeds is minimal. An average increment of 7% was noticed for all speeds for changing the LPG fraction from 25% to 30% at all CR; this rate of change is reduced to 4% for the LPG fraction changed from 40% to 45%. The impact of CR is more significant compared to other changes; there is an average 12.73% change in CO at 1400 rpm for CR12 to CR13, which reduces to 8.37% for CR14 to CR15; however, increasing speed decreases the extent of CR change on CO, as at 1800 rpm, the average reduction in CO is reduced to 11.35% for CR12 to CR13 which further reduced to 7.19% for CR14 to CR15. Increasing CR improves combustion quality and reduces the chance of incomplete combustion. However, with low LPG fractions, incomplete combustion is more possible. At a high LPG fraction, the increasing CR raises the probability of disassociation along with the combustion quality, which finds itself out of dominance, results in a decrease in CO and a

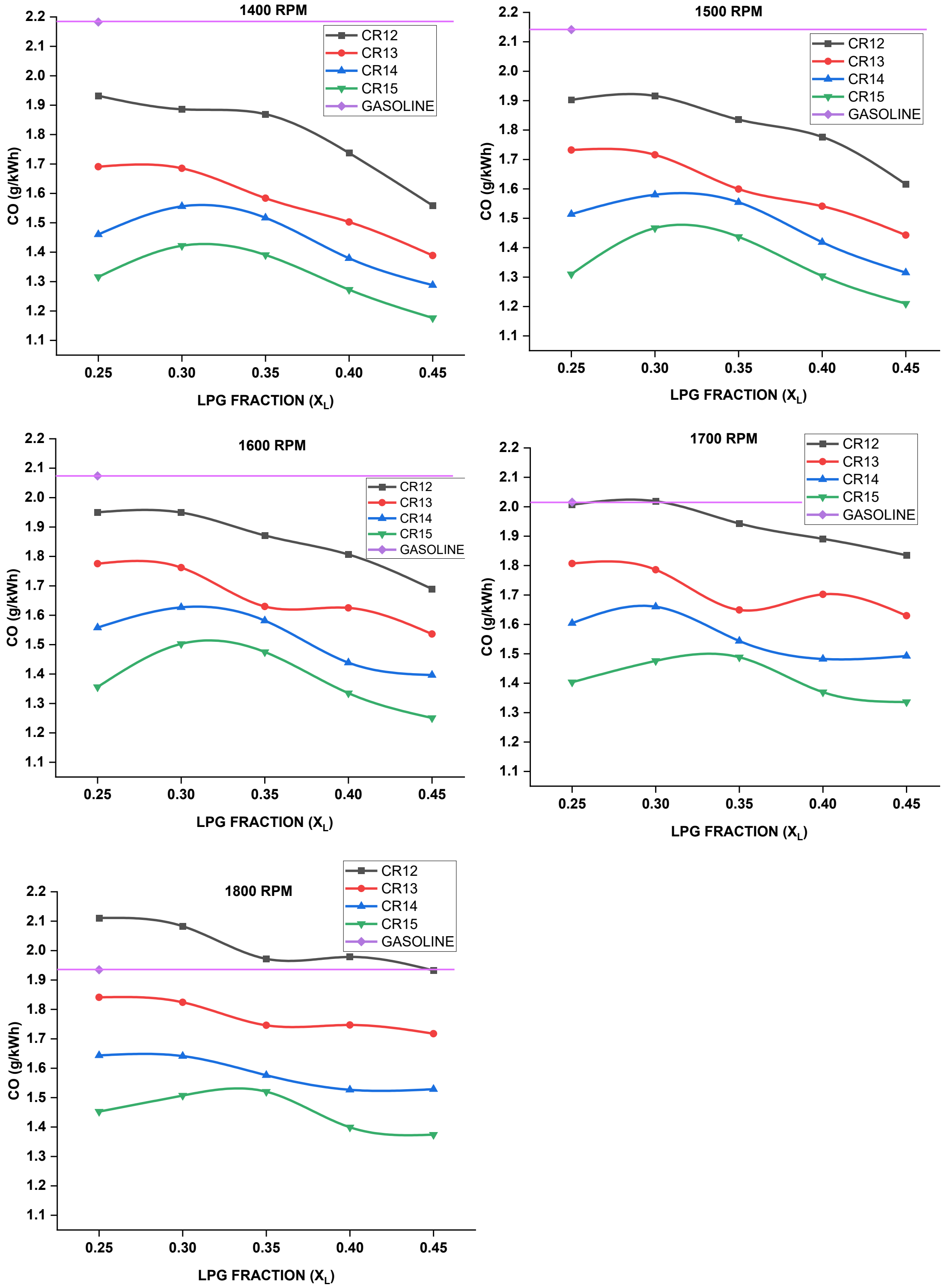
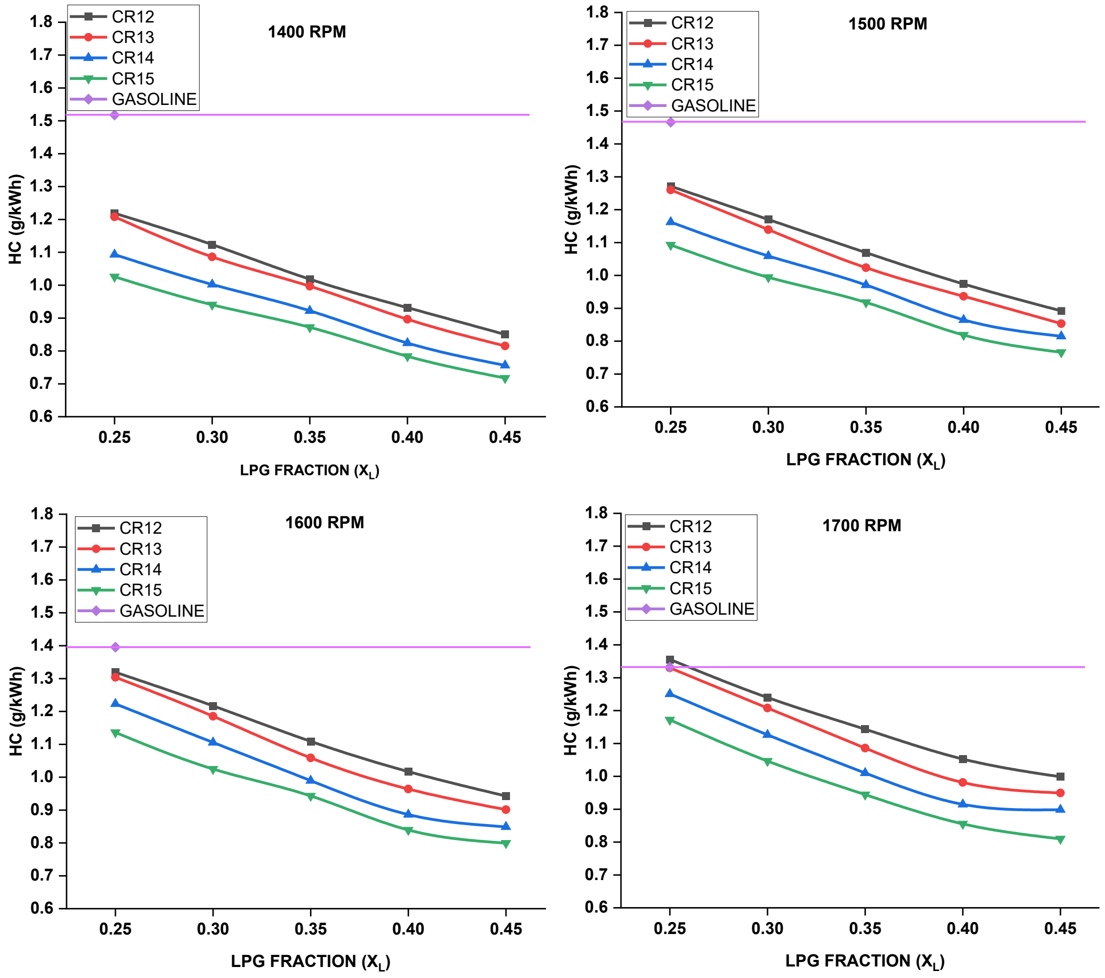


Figure 4.7 CO emissions variations with LPG fractions and CR at different speeds

decrease in the reduction rate. Due to oxygen's presence in the molecular structure, the higher oxygen concentration in blended fuels and the enhanced mixing at high temperatures are adequate for CO_2 generation. Therefore, the results show a reduction in CO emissions relative to gasoline.

Unburned hydrocarbon emission

Figure 4.8 shows that, at low speeds, HC emissions drop continuously with increasing LPG fractions, indicating incomplete combustion. However, after a specific LPG fraction increase limit, HC emissions increase slightly at high speeds, possibly due to a reduced air-excess ratio and less available time compared to gasoline. There is an average decrease of 1.89% to 1.34% per 5% change in LPG for CR 12 to 15 at 1400 rpm, which decreases to 0.05% to 1.23% per 5% change in LPG for CR 12 to 15 at 1800 rpm.



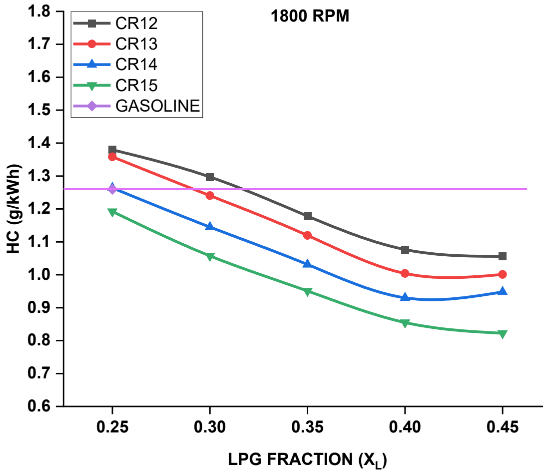


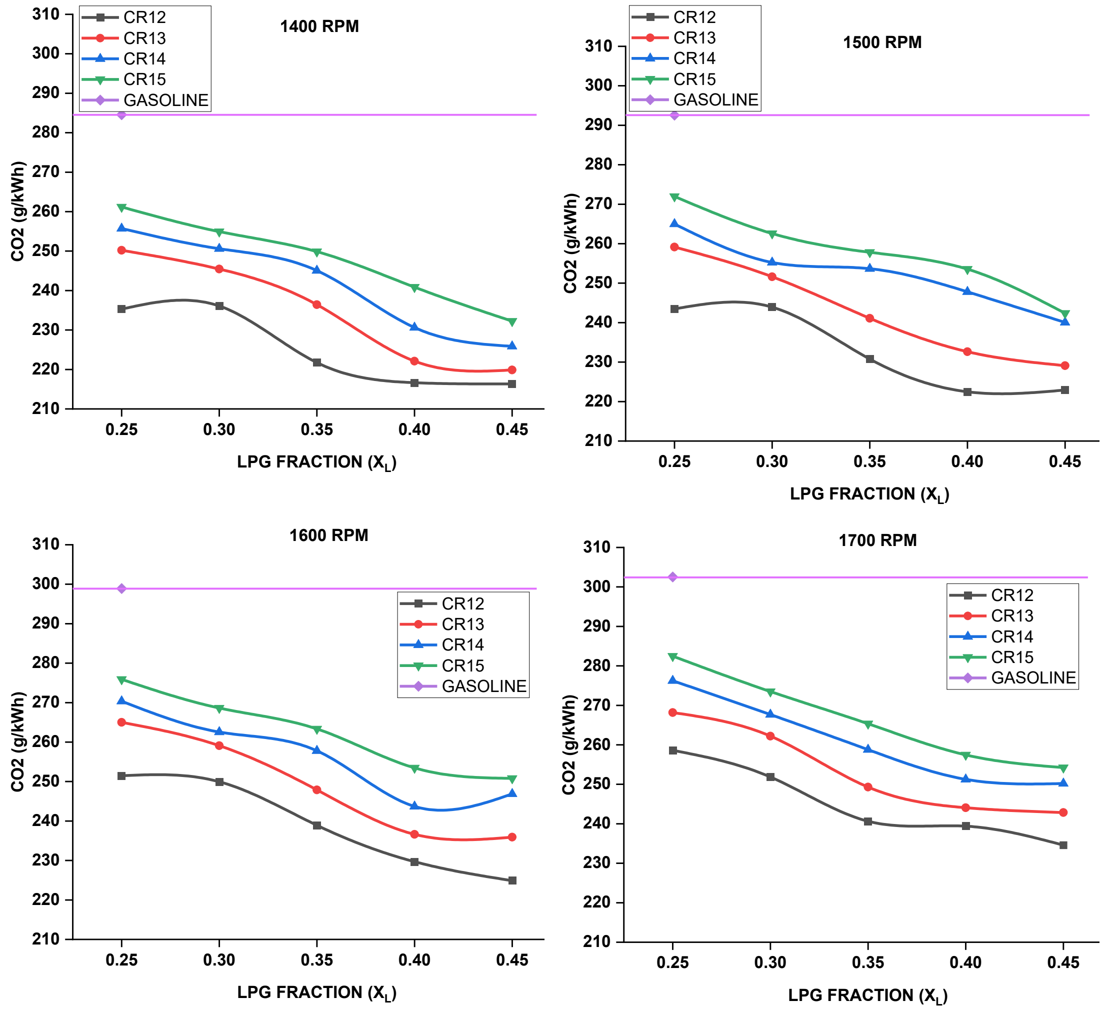
Figure 4.8 HC emissions variations with LPG fractions and CR at different speeds

The impact of altering CR is greater than changing LPG fraction, as a near 5.4% decrease per CR is observed at 1400 rpm for all LPG fractions. The rate of decrease increases with increasing speed and is approximately 6.34% per CR at 1800 rpm for all LPG fractions. Increasing speed is reported to be responsible for greater HC emissions due to reduced available time for combustion; however, this effect is less noticeable at low LPG concentrations. At CR12, the increase in speed from 1400 to 1500 rpm is 4.31% for a 25% LPG fraction, while it is 7.94% for the same speed change at the same CR for a 45% LPG fraction. All speed changes followed the same trend at the same CR. Increasing the CR, this increment is diminished; at CR 15, the rate of increase is lowered to an average of 2.96% for all speed changes.

Carbon dioxide emission

Unlike CO and HC, CO_2 emission is indicative of the level of complete combustion, as shown in Figure 4.9. CO_2 increases with increasing LPG fractions; as the air-excess ratio drops, the quality and possibility of combustion increase (Chen et al. 2019a). However, the rate of increase decreases when LPG strength, speed, and CR rise. A near 6.42% rise was seen when the LPG fraction was increased from 25% to 30% at all CR12 and speeds; however, the increase was reduced to 5.25% when the LPG fraction was increased from 40% to 45% at all CR12 and speeds. Increasing the CR to 15 lowers this rate to near 5% for all speeds for all successive LPG fraction changes. The increased CR raises the pressure and temperature at ignition, accelerates combustion, and raises CO_2 emissions (Balki and Sayin 2014).

Similarly, an increase in speed causes an increase in thermal properties, which improves the quality of combustion and results in an increase in CO_2. For 25% LPG, the rate of increase in emissions varies from 5% per 100 rpm to 4% per 100 rpm as engine speed changes from 1400 rpm to 1800 rpm at CR 12 but remains nearly constant at all CRs. However, an increase in the LPG percentage raises this rate of change at low speeds up to 1600 rpm to around 6% per 100 rpm, while it reduces somewhat to approximately 4% per 100 rpm at CR12 and remains constant over CR change. Comparing the combined effect of LPG fraction and CR at any speed reveals a net rate of rise of 34.33%, ranging from 25% LPG at CR12 to 45% LPG at CR15; this rate of increase is nearly constant across all speeds. In this instance, the drop in CO_2 is caused because methanol contains less carbon than gasoline.



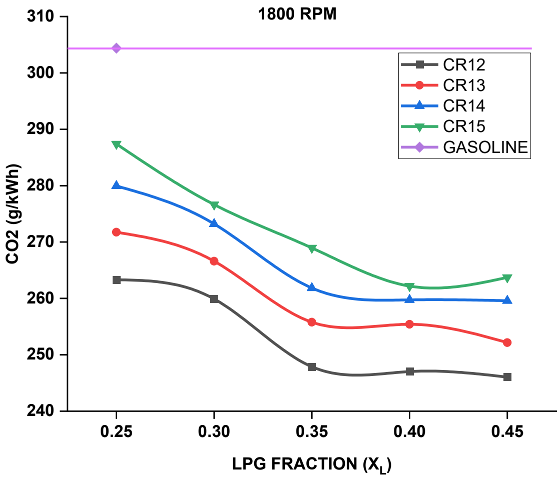


Figure 4.9 CO_2 emissions variations with LPG fractions and CR at different speeds

Oxides of nitrogen emissions

Figure 4.10 shows NOx emissions, which are shown to increase continuously with increased LPG fractions as the total contributed energy increases, and EGT is also found to increase, showing that the increased peak cylinder temperature is the cause of NOx generation (Li et al. 2017; Wang et al. 2019). NOx is shown to increase with increased speed, partly due to a rise in mean gas temperature (Bayraktar and Durgun 2005). There is a 20% increase found at 25% LPG at CR12 for increasing speed from 1400 rpm to 1500 rpm, which decreases with LPG fraction and is found to be 10% for changing speed from 1700 rpm to 1800 rpm under the same conditions; the rate of increase decreases with increasing speed as it ranges from 14.76% to 8.1% when changing speed from 1700 rpm to 1800 rpm at CR12. In addition, as CR increases, the rate of increase at lower LPG fractions decreases and increases at higher LPG fractions. Increasing CR results in a rise in mean cylinder pressure and temperature, which in turn leads to a rise in peak cylinder temperature and a rise in NOx formation (Balki and Sayin 2014). At 1400 rpm, the average rise of each CR is close to 10%, while at 1800 rpm, the average increase per CR is 11%. At 1400 rpm, a change from 25% LPG at CR12 to 45% LPG at CR15 results in a 229% increase in NOx. At 1800 rpm, this rate of increase decreases somewhat to 209%. Methanol's high latent heat reduces the cylinder's temperature, resulting in a lower NOx output than gasoline.

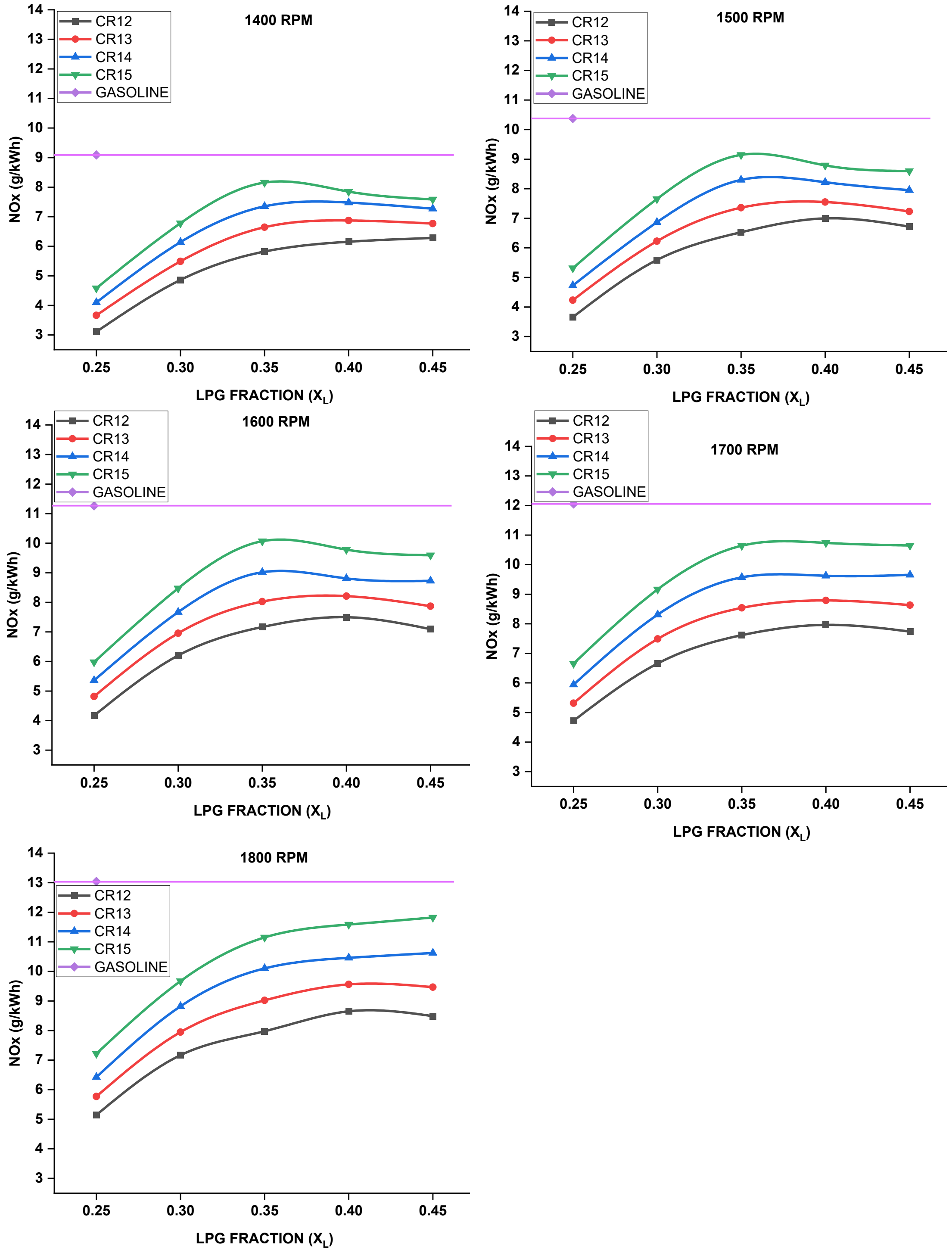


Figure 4.10 NOx emissions variations with LPG fractions and CR at different speeds

4.2 Influence of CR and blending ratio (Ammonia/Hydrogen)

The experimental outcomes are compiled based on speed for each CR and hydrogen energy fraction. Following is a discussion of the analysis of these experimental results by graphical representation with probable cause;

4.2.1 Brake power

BP is a function of speed, as shown in Figure 4.11, as BP increases with increasing speed (Hagos et al. 2019). BP is also shown to rise constantly with rising CR at any speed, as the increase in CR lowers the cooling effect of ammonia by raising the mean cylinder temperature and pressure (Balki and Sayin 2014). On the other hand, ammonia has a low BP due to its low flame speed and low combustion temperature, offset by hydrogen (Frigo et al. 2012). Here, increasing hydrogen fraction is responsible for increasing BP despite the same fuel energy supplied at any speed and CR. However, this effect reduces gradually with increasing CR and engine speed. At 1400 rpm and CR 12, a 14.2% increment in BP from 5% to 21% hydrogen fraction chance increases to 15.77% at CR15 at the same speed. However, at 1800 rpm, there is a 10.66% increment at CR12 for the exact hydrogen fraction change, which reduces to 10.34% at CR15. However, the BP of gasoline is larger than any fuel combination, which is all due to the total energy supplied by the gasoline being more than the fuel. Since the volumetric energy density of gaseous fuel is less, the calorific value of ammonia is also lower than gasoline, which results in low fuel energy supplied. On the other hand, the volumetric losses due to hydrogen are compensated to an extent by the cooling effect of ammonia; hence, the relative drop in BP at high hydrogen fraction is less.

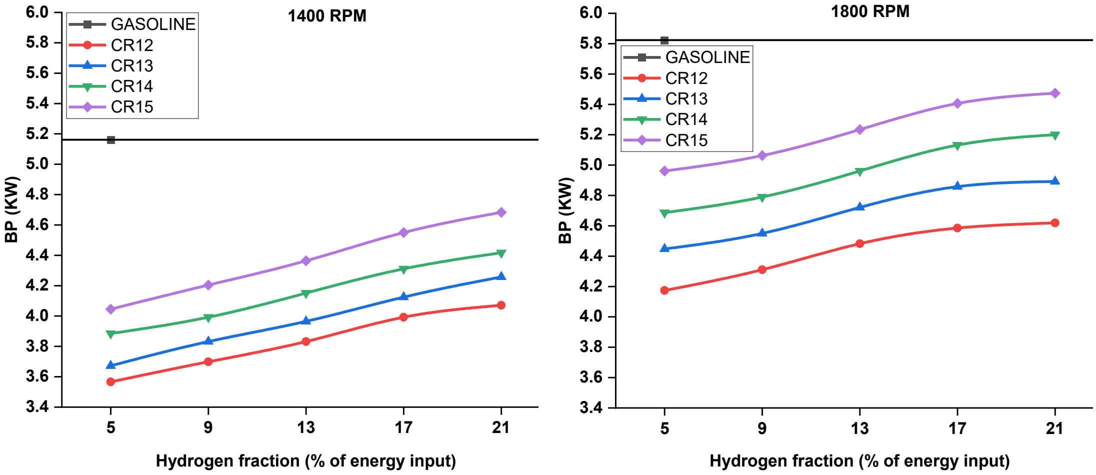


Figure 4.11 Variations in BP with CR and hydrogen energy fractions at 1400&1800 rpm

4.2.2 Brake thermal efficiency

Ammonia is a slow-reacting substance; it leads to a longer combustion duration, responsible for inefficient combustion and the loss of thermal efficiency. However, the heat losses from the cylinder wall are reduced, and the thermal efficiency is improved(Comotti and Frigo 2015). Figure 4.12 depicts a graphical comparison of BTE at 1400&1800 rpm speeds. Higher speed increases the temperature of the combustion chamber, which raises the temperature of the intake charge. It reduces the mass of the working fluid in the combustion chamber, resulting in a low work output per unit cycle and a lower BTE. At a low-speed of 1400 rpm, increasing CR from 12 to 15 increases BTE by 6.42% at a hydrogen energy fraction of 21%, but only by 5.93% at a hydrogen energy fraction of 5 percent. Because of its higher flame speed, which results in a faster heat release rate, the BTE increased by adding hydrogen energy, assisting in working the engine in better condition. A higher hydrogen energy fraction increases the energy supplied inside the engine cylinder and reduces the negative effect on BTE caused by ammonia latent heat of vaporization. The maximum BTE obtained at 1400 rpm is 31.13% and at 1800 rpm is 30.14%. The fraction of residual gas increases at higher speeds, the induced volume decreases, and thermal efficiency is low. The slow-reacting character of ammonia can be seen at low hydrogen fractions, resulting in low BTE despite increasing CR. As the hydrogen fraction increases, the combustion quality improves, resulting in more efficient fuel burning and higher BTE. Apart from that, the increasing CR reduces the latent effects of ammonia and reduces the combustion duration, which results in fast combustion, so the BTE is improved (Sakthivel et al. 2020b). In addition, the increasing hydrogen fraction at a high compression ratio diminishes the drawback of ammonia and

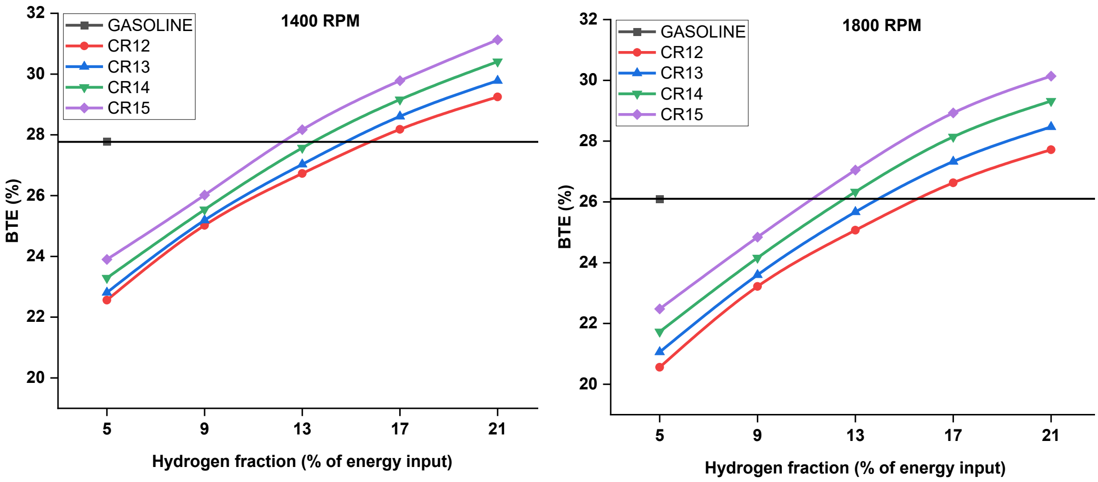


Figure 4.12 Variations in BTE with CR and hydrogen energy fractions at 1400&1800 rpm

the low quenching distance, allowing the flame to travel near to cylinder wall. Hence, a large mass is burnt, leading to an increase in BTE. Another factor impacting BTE is using a lean burning strategy (Wang et al. 2021b). While compared to gasoline, the BTE is improved with increased hydrogen and CR.

4.2.3 Volumetric efficiency

Ammonia vapor is lighter than air; hence, it replaces instream air, reducing η_{vol} (Schramm et al. 2020). However, the latent effect of ammonia is responsible for cooling the instream charge, leading to an increase in the $\eta_{vol;}$ the cooling effect of any fuels in the instream air influences the increase in η_{vol} (Dinesh et al. 2022a). Figure 4.13 depicts the combined effect: at a lower speed, the cooling effect of ammonia dominates, resulting in a maximum η_{vol} of 74.55% at 12CR and 5% hydrogen energy fraction, but at a higher speed, the η_{vol} drops to 59.55% in similar conditions. With increasing CR, the residual gas fraction (RGF) reduces, leading to an increase in η_{vol}, which is more than gasoline at low speed and low hydrogen fraction. The increasing speed increases the amount of RGF and the mean cylinder temperature, which is responsible for reducing the cooling effect of ammonia. As a result, the η_{vol} starts to drop. For the entire range of hydrogen energy fraction, there is an average decrease in η_{vol} of 10.58% & 19.53% at 1400 rpm&1800 rpm, respectively. The proportion of hydrogen fraction η_{vol} decreased. Increasing the strength of hydrogen η_{vol} reduces rapidly because the gaseous form and high hydrogen diffusivity replace a large amount of air. When the CR is raised, the η_{vol} rises; however, the effect is reversed when the speed is raised. With increasing CR, the residual gas fraction (RGF) decreases, resulting in an increase in η_{vol} along with CR, but vice versa in the case of speed; thus, the boost averaged value of η_{vol} is 4.69% at 12CR to 15CR and 5% hydrogen energy fraction in 1400 rpm. Gasoline is a liquid fuel, which gets vaporized during suction stroke; hence the instream air gets cooled, and the η_{vol} is not suffering the RGF effect due to increasing speed as much as ammonia/hydrogen. Hence, at high speeds, the η_{vol} of gasoline is found to be better. However, the effective stoichiometric air requirement of the fuel combination is very low compared to gasoline; the BTE is not found to get stressed by reducing η_{vol}.

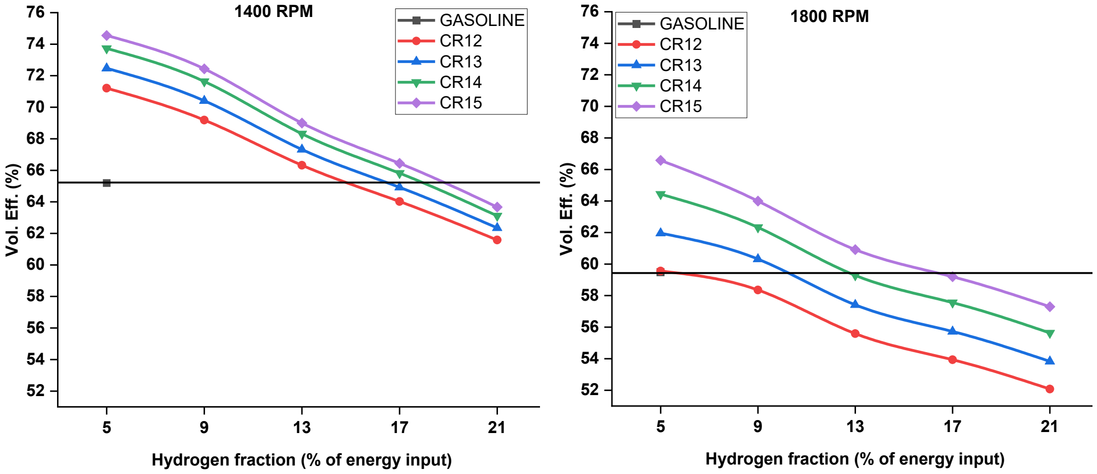


Figure 4.13 Variations in η_{vol} with CR and hydrogen energy fractions at 1400&1800 rpm

4.2.4 Maximum cylinder pressure

The ignition timing is kept the same for both gasoline and ammonia/hydrogen fuel blend despite the different combustion nature of the fuels. Gasoline is a fast-burning substance compared to ammonia/hydrogen blends; therefore, a larger mass burns before TDC, resulting in increased pressure during the compression stroke and the P_{max}. In addition, the total energy supplied by gasoline is higher than blended fuel, which is also responsible for increasing P_{max}. However, the gap between gasoline and blends is reduced with increasing hydrogen fraction. Hence, the P_{max} of blends increases as the hydrogen fraction increases due to a better thermodynamic atmosphere inside the combustion chamber, a portion of the exothermic heat before TDC, and an increase in exothermic concentration (Xin et al. 2022). The blend burns faster because hydrogen has a faster laminar flame speed than any other fuel, resulting in fast combustion and rapid release of energy, increasing the pressure and temperature; therefore, P_{max} is increased. P_{max} rises by 8.7% and 10.24% at 1400 rpm for 5% and 21% hydrogen energy fraction variable CR, respectively, while at 1800 rpm, it rises by 15% and 16%, depicted in Figure 4.14.

Similarly, increasing CR increases the mean cylinder temperature and pressure, increasing the P_{max}. The increase in CR also improves the η_{vol}, allowing more air. Therefore, more fuel can be supplied, and the combustion efficiency increases, resulting in an increased P_{max}. On the other hand, with increasing speed, P_{max} is observed to increase; at a lower speed, the overall increment of P_{max} is 25.95%, and at a higher speed, it increased to 28.38%, probably due to insufficient cooling; the mean cylinder temperature, and pressure increase. However, there is a significant reduction in volumetric efficiency with increasing speed and ammonia's very low laminar flame speed, which restricts pressure and temperature slightly (Ryu et al. 2014), resulting in an increased gap between gasoline and blended fuel.

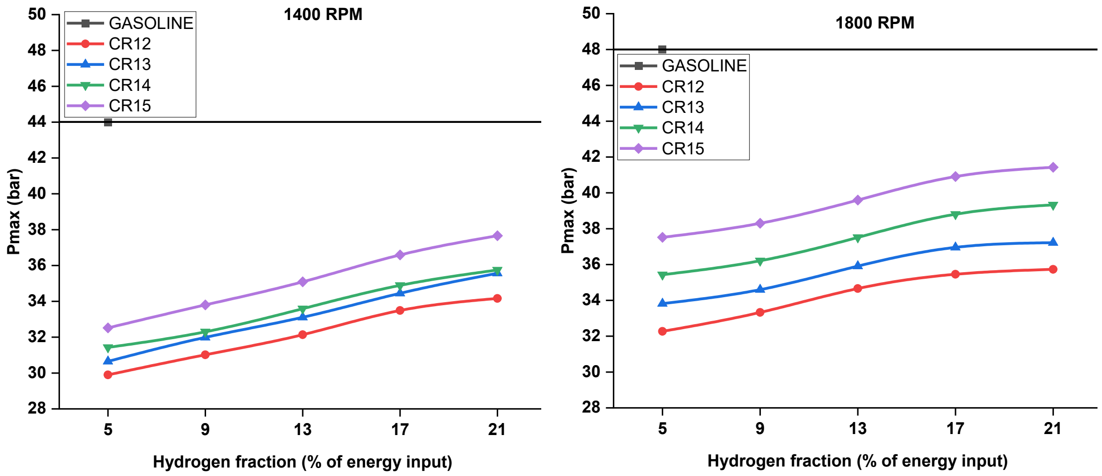


Figure 4.14 Variations in P_{max} with CR and hydrogen energy fractions at 1400&1800 rpm

4.2.5 Maximum Net Heat Release Rate

Maximum Heat Release Rate is essential for predicting flame propagation effects. Peaks of the heat release rate (NHR_{max}) are shown in Figure 4.15 at speeds 1400&1800 rpm. It is observed that the increasing speed increases NHR_{max} due to improved burning speed. Similarly, increasing the CR reports faster combustion, resulting in a relatively large mass burnt in a shorter duration. Changing the CR from 12 to 15 results in an increase of 28.84% at 1400 rpm, which rises to 36.38% at 1800 rpm. Therefore, the NHR_{max} is increased with increasing CR as well as speed. The OH×N radicals significantly influence the NHR_{max} when adding different hydrogen fraction conditions (Li et al. 2019). In the case of ammonia, though increasing CR improves the combustion, it is still found very slow at low hydrogen fractions, which results in a very low HRR_{max} compared to gasoline. The combustion phenomenon further improves with increasing the hydrogen fraction, resulting in short combustion periods. Hence, the NHR_{max} starts improving, reducing the gap between gasoline and blend. As the spark timing is fixed, the flame speed increases with increasing hydrogen fraction. A large mass is burnt before TDC, which raises the temperature and promotes flame speed.

Hence, a relatively higher rate of heat release and NHR_{max} is increased. With increasing speed, this extent of improvement with hydrogen fraction increases, and the gap is shortened.

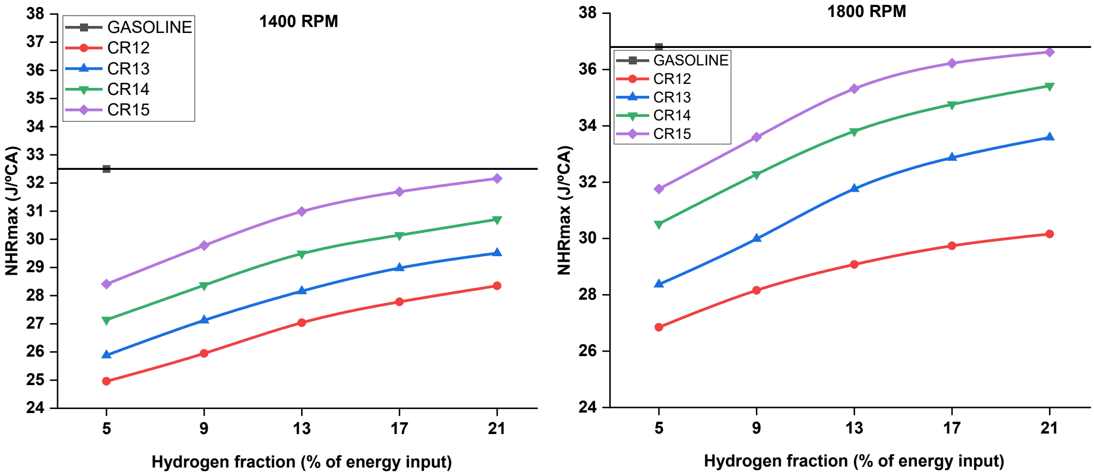


Figure 4.15 Variations in NHR_{max} with CR and hydrogen energy fractions at 1400&1800 rpm

4.2.6 Exhaust Gas Temperature

EGT reflects the rate of heat released in the combustion chamber (Atmanli and Yilmaz 2020). A slow-burning fuel results in a long after-burning period, which increases the exhaust gas temperature. In addition, a high quenching distance does not allow effective heat deposition to the cylinder wall, which also increases the exhaust gas temperature. These two effects are prominent in ammonia combustion and can be seen in Figure 4.16. However, with increasing CR, the burning speed improves, reducing the EGT.

Similarly, increasing hydrogen fraction initially reduces the EGT due to increased combustion speed and a reduction in quenching distance. However, increasing the hydrogen fraction after some specific limit increases and dominates the mean cylinder temperature. The η_{vol} also gets reduced, which suffers lesser mass at a relatively higher temperature, increasing the cylinder temperature. Therefore, the EGT increases with a higher hydrogen fraction. This effect dominates with increasing speed, as the increasing speed reduces efficient engine cooling, which results in increased cylinder temperature, and hence, the EGT starts increasing. On the other hand, compared to gasoline, blended fuel is found to have a larger EGT; this may happen due to the long after-burning period compared to gasoline, which allows some mass to burn at the late expansion stroke;

hence the EGT is larger compared to gasoline. However, increasing the speed on gasoline is more severe than ammonia/hydrogen; hence, the EGT is larger for gasoline in most of the blend ratios.

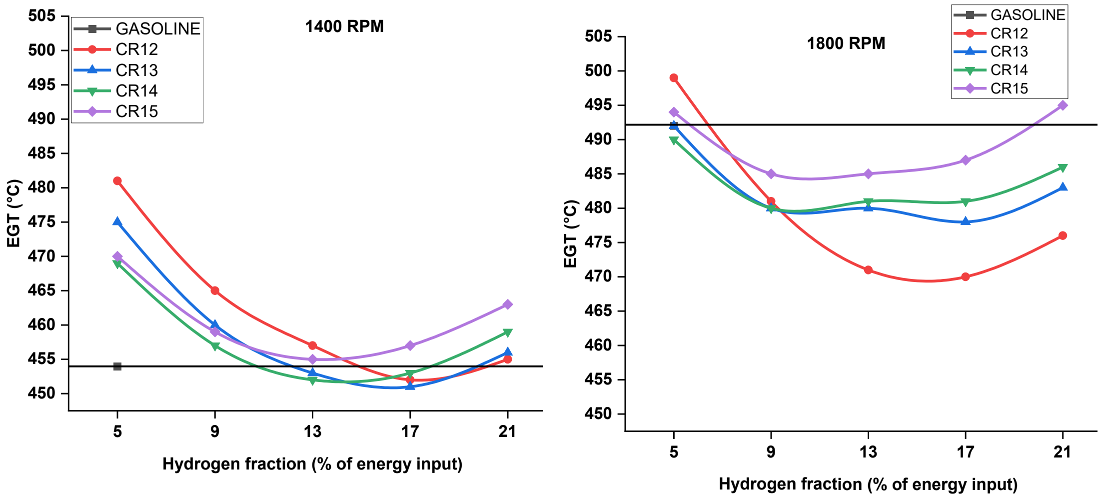


Figure 4.16 Variations in EGT with CR and hydrogen energy fractions at 1400&1800 rpm

4.2.7 Oxides of nitrogen emissions

Ammonia is a carbon-free but nitrogen-dominant compound. Hence, the carbon-based emissions are negligible, while nitrogen-based emissions are constituted mainly by oxides of nitrogen (NO_x) exceptionally high compared to gasoline. There are two kinds of NO_x emissions in ammonia/hydrogen, first due to the natural combustion of ammonia (as oxidation products) and another due to the high adiabatic temperature of hydrogen. At the low hydrogen fractions, ammonia-based NO_X is a significant contributor, accompanied by T_{max}-motivated NO_x by increasing the hydrogen fractions (Joo et al. 2012). However, with an initial increase in hydrogen, the T_{max} is not rising rapidly, resulting from slow combustion. Hence, the NO_X emissions are increasing insignificantly at low speed and minutes at high speed. With increasing CR, the effect of hydrogen addition comes in calculations extensively, even at low fractions.

On the other hand, increasing CR on NO_x emissions starts reducing with increasing hydrogen fractions, as sown in Figure 4.17. The hydrogen addition effect and lean burning conditions on NO_x formation dominate CR at higher fractions and speeds (Lesmana et al. 2019). However, a summarized outcome is that the NO_x formation due to ammonia is enhanced with CR due to increased supply; this is accompanied extensively by the hydrogen addition at higher speed and hydrogen fraction due to a rapid increase in adiabatic flame temperature, leading to increased T_{max}. However, NO_x emissions are not a problem because, in the case of a stoichiometric mixture, NO_x can be effectively abated by a normal, reducing catalyst and, in the case of a lean mixture, the presence of ammonia on board makes the use of an SCR easier.

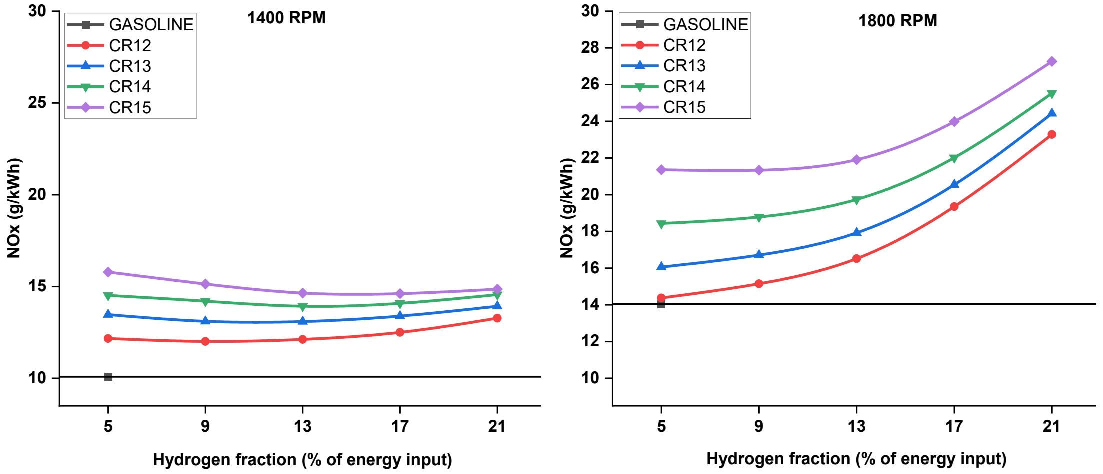


Figure 4.17 Variations in NO_x with CR and hydrogen energy fractions at 1400&1800 rpm

4.3 Influence of ignition timing and CR (Ammonia/Hydrogen)

The experimental results for all CR and ignition timing are compiled based on speed. All of the experiments are carried out under similar conditions. For comparison, the test results are grouped by the two speeds. The findings are organized below by the major comparable parameters;

4.3.1 Brake power

The ignition timing is an important variable in optimizing engine performance. Figure 4.20 depicts the variations in BP induced by ignition timing and CR. At both speeds, enhanced ignition timing has been recorded to boost BP by up to 28ºCA bTDC. When the engine was fueled with ammonia/hydrogen, various ignition timing and compression ratio (CR) tests were carried out. It has been noted that a reduction in brake power resulting from the use of ammonia/hydrogen dual fuel can be offset by changing the ºCA before the top dead center to some extent. Spark advance significantly influences output factors like power and efficiency, which can be helpful for performance. BP is proportional to torque. Therefore, as torque increases, the brake power also increases. When the ignition timing is altered from 18ºCA to 32ºCA bTDC, the BP increases with CR and speed. The CR improves volumetric efficiency, boosts cylinder temperature, and reduces pumping losses, enabling the engine to ignite more fuel and generate more power. When the ignition timing was altered from 18ºCA to 32ºCA bTDC, the maximum percentage increase in BP at low speeds was 19.59%, 22.06%, and 24.60%, respectively, at CR 14, 15, and 16.

Similarly, the corresponding percentages at high speeds are 22.68%, 24.77%, and 25.13%. As engine speed increases, the more total energy is drawn into the cylinder, which improves brake power. At CR 14 to 16, the maximum amount of BP produced at 1400 rpm is 35.11%, while at 1800 rpm it is 36.82%. With ignition timing of 28ºCA bTDC and 16CR, the highest BP value at lower speeds is 5.1586 kW. Similarly, a BP maximum of 6.12 kW is attained when the speed is increased. The results reveal that the most power is generated when the ignition timing is advanced by 28ºCA bTDC, which results in the highest BP value for varying CR and engine speed (1400&1800 rpm).

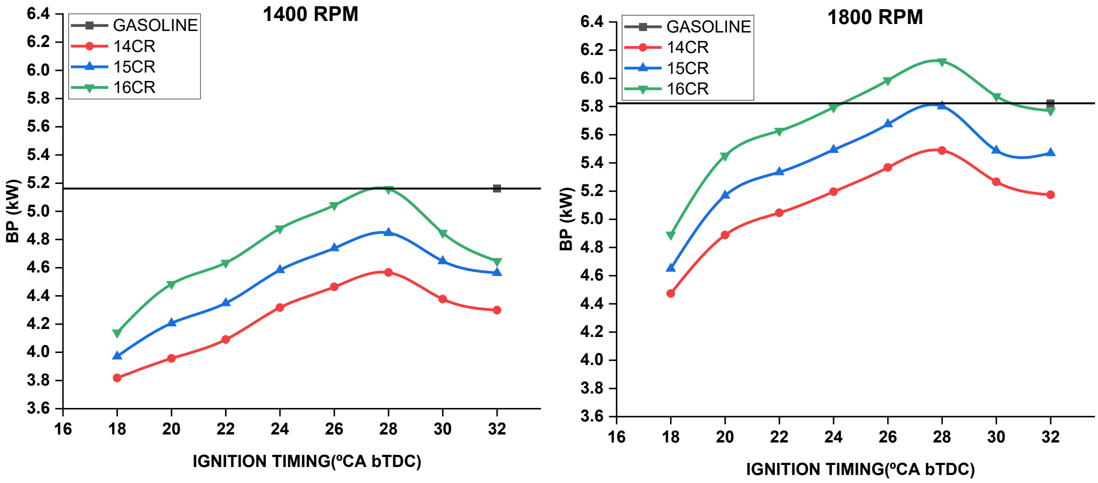


Figure 4.18 BP Variations with CR and ignition timing at 1400 & 1800 rpm speeds

4.3.2 Brake thermal efficiency

The brake thermal efficiency is essential because it describes how the engine transforms fuel into BP. Figure 4.21 depicts the influence of altering ignition time with CR on BTE for SI engines operating between 1400 and 1800 rpm. The graphs show that when the ignition timing was advanced up to 28ºCA bTDC, the BTE increased steadily and then decreased. As compression ratios increase, the pressure and temperature within the combustion chamber increase, resulting in higher combustion efficiency. Due to the enhanced thermal efficiency, a rise in CR leads to improved fuel economy. It is noticed that the BTE of the engine increases with increasing CR up to CR 16. Adjusting the ignition timing from 18ºCA to 32ºCA bTDC increased the BTE at low speeds by an average of 22.83% for CRs 14, 15, and 16.

Similarly, at high speeds, the values are 21.81%. At 1400 rpm, the maximum percentage of BTE produced is 25.11%, while at 1800 rpm, it is 23.71%. At 1800 rpm, the available time for combustion is significantly reduced, resulting in a decrease in BTE. Another factor contributing to NH_3's high latent heat is the cooling of the working fluid, which reduces compressive work and consequently raises BTE. Dual fuel operation also enhances BTE; the improvement is most pronounced at 28ºCA bTDC due to the enhanced combustion rate resulting from ignition advance. It is concluded that ignition timing significantly impacts the combustion process and the BTE. The spark advance substantially affects performance characteristics such as output and efficiency (Ortiz-Imedio et al., 2022).

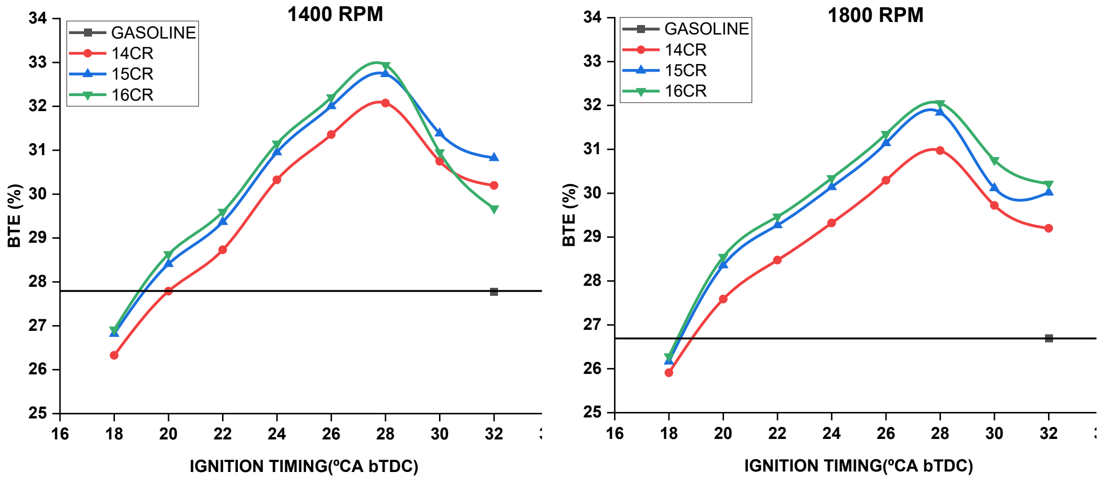


Figure 4.19 BTE Variations with CR and ignition timing at 1400&1800 rpm speeds

In conclusion, the effect of advanced ignition timing, hydrogen, and compression ratio on accelerating combustion leads to more concentrated heat release processes and a higher BTE for ammonia/hydrogen fuel than gasoline. With a reasonable advance in the spark timing, the BTE increases. However, excessively advancing the spark timing will significantly raise the load through compression work and heat transfer loss. As a result, when the spark timing is advanced too far, the BTE decreases at 30 to 32 °CA bTDC. Peak BTE (32.94%) is achieved under all conditions tested at 16CR and IT of 28 °CA BTDC.

4.3.3 Volumetric efficiency

Figure 4.22 displays the η_{vol} of an ammonia/hydrogen fuel engine under WOT conditions with variable ignition time, CR, and engine speed. As the intake airflow becomes suffocating and the available time for fuel evaporation decreases, increasing the vehicle's speed has a higher effect on η_{vol}. Since increasing speed decreases the time for the exhaust stroke to complete, the residual gas fraction (RGF) and exhaust manifold pressure increase in the combustion chamber, resulting in a lengthy expansion of RGF, shortening the intake length. Along with this, the suction stroke duration decreases at high speed, resulting in a loss of volumetric efficiency, which is reflected by a decrease in the BTE at high speed. In contrast, CR increases the pressure and temperature within the engine cylinder and decreases the concentration of residual gases, resulting in a greater η_{vol}. It is noted that the η_{vol} maximum is at 28ºCA bTDC and then decreases at both sides of advanced and delayed ignition timing. As the input mass flow rate increases at 28 ºCA bTDC, volumetric efficiency and BMEP have increased with rising ignition timing (Zareei and Kakaee 2013). At lower speeds, the average η_{vol} increase for various ignition timing and CR is 8.57%, while at higher speeds, it is 7.55%. On the other hand, advancing the ignition time results in a prolonged combustion period due to challenges in flame growth as a result of inadequate pressure and temperature in the combustion chamber, which also results in a decrease in volumetric efficiency.

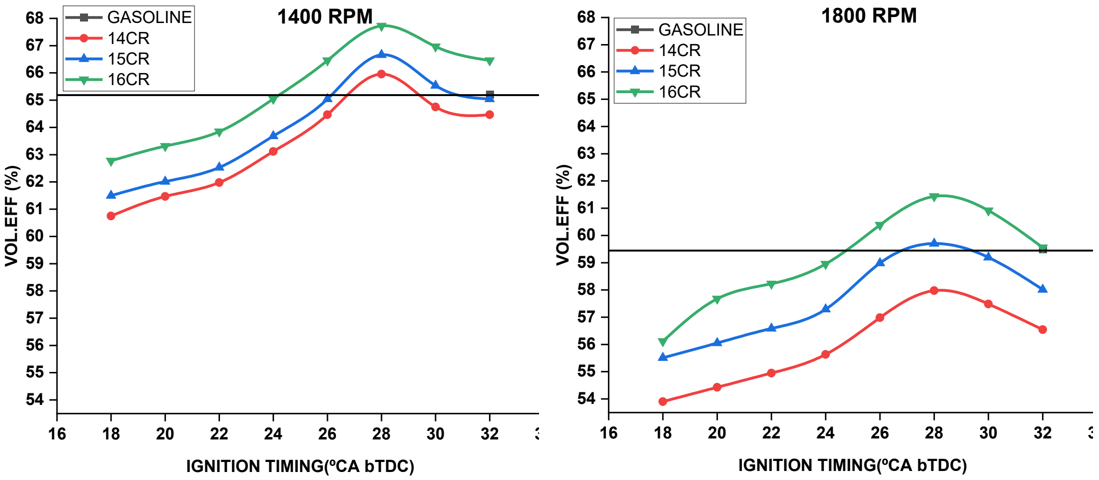
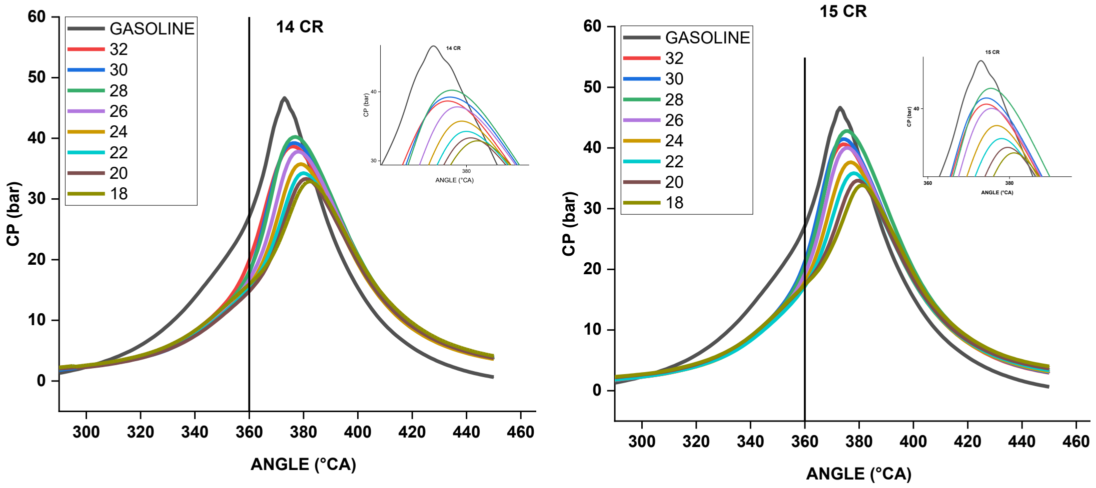


Figure 4.20 η_{vol} Variations with CR and ignition timing at 1400&1800 rpm speeds

Due to the charge cooling effect of ammonia fuel, the in-cylinder charge has the advantage of lowering the temperature, so improving volumetric efficiency can also raise the BTE (Dinesh et al. 2022b). Eventually, the residual gas and gas-exchange process would affect the η_{vol}. In addition, regardless of the CR, increasing engine speed decreases engine η_{vol}, and the improved η_{vol} is consistently seen at 1400 rpm.

4.3.4 Cylinder pressure

In order to gain a better understanding of the combustion process, we studied the cylinder pressure at various spark timings, CR, and speeds of 1400 rpm and 1800 rpm at each experimental stage as shown in Figure 4.21 and 4.22. Therefore, the optimal timing for combustion is determined to exist. High cylinder pressure is produced via optimal timing, with the peak occurring after TDC. It ensures that the expansion stroke has minimal compressive work and maximal work shifts (Hotta et al. 2019); as peak pressure approaches TDC, the probability of work output increases. Compared to IT of 18 ºCA bTDC, IT of 28 ºCA bTDC increases the peak pressure by almost 9.45% at 1400 rpm and 10.35% at 1800 rpm. The peak pressure for both speeds was observed at 28 ºCA bTDC compared to other ignition timings, which is the optimal time for combustion. Despite the lower heating value and density of the ammonia fuel, it has been determined that the rise in peak cylinder pressure is due to the addition of hydrogen, altered ignition timings, and a higher CR. During this period, which has enhanced the amount of isochoric combustion, sped up combustion, and worked to burn the mixture completely.



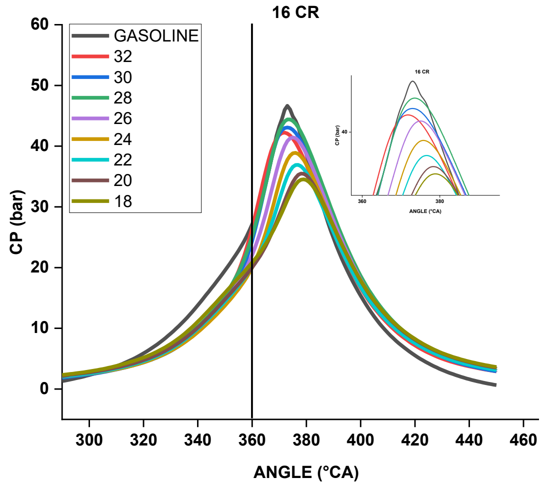


Figure 4.21 Variations in CP with CR and Ignition Timing at 1400 rpm

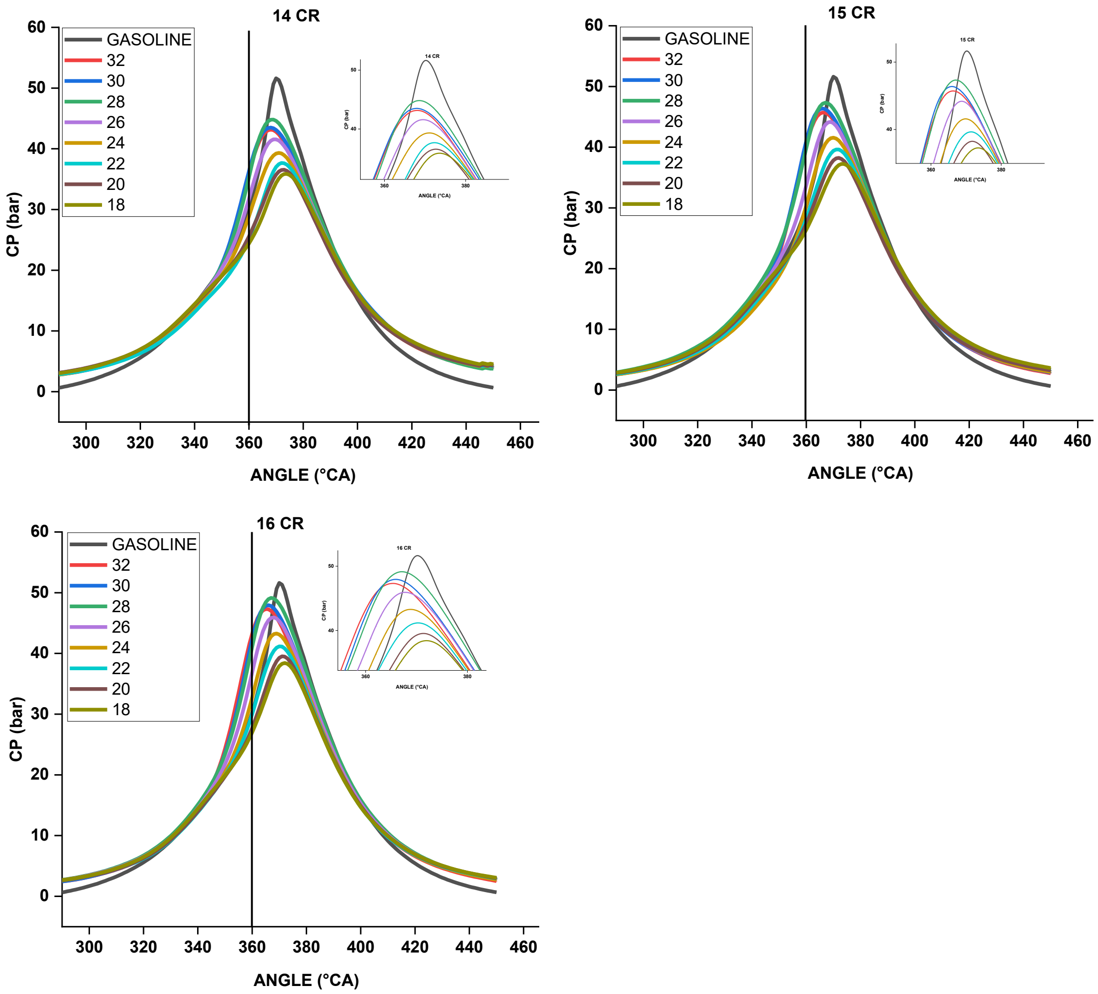
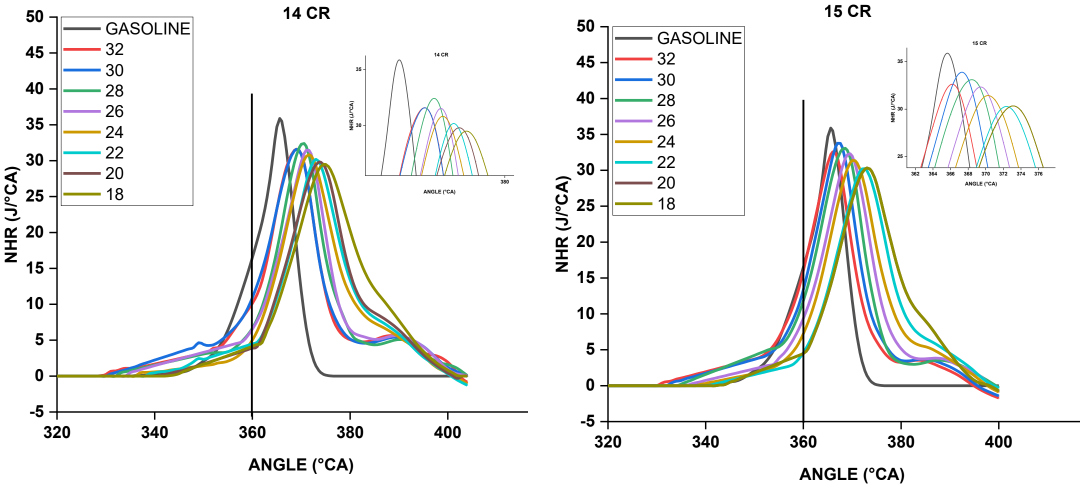


Figure 4.22 Variations in CP with CR and Ignition Timing at 1800 rpm

The combustion process is substantially increased due to the high laminar flame speed of hydrogen and the high volumetric efficiency of ammonia. In contrast, the internal pressure of the cylinder and the combustion angle is found to be advanced. High cylinder pressure is the most important factor in combustion analysis, as it reflects the engine's operational efficiency. Due to the charge-cooling action of ammonia, the cylinder pressure of ammonia/hydrogen fuel is slightly lower than that of gasoline.

4.3.5 Net heat release rate

Figures 4.23 and 4.24 show the differences in NHR for different IT and CR concerning speeds. The rate of heat release reflects the quality of the combustion. The graphs show that the NHR rises continually with increasing speed. When the IT is changed from 18 ºCA to 28 ºCA bTDC, the maximum heat release rate increases by 8.49% at lower speeds and 9.53% at higher speeds. When the IT is advanced from 18 ºCA to 32 ºCA bTDC, the NHR rises gradually at any speed up to 28ºCA bTDC. The peak NHR for both speeds were observed at 28 ºCA bTDC compared to other ignition timings, which is the optimal time for combustion. However, the combustion deteriorates at ignition timing 30 to 32 ºCA bTDC because combustion phasing advanced excessively. NHR is primarily determined by combining a fuel's latent heating value and combustion efficiency. The higher heating value and combustion efficiency of gasoline lead to a greater NHR than ammonia/hydrogen fuel. The highest HRR also tends to increase as spark timing advances. A suitable advance in IT may cause an increase in fuel burned near the TDC. This implies that more heat will be released in a small combustion chamber, leading to more isochoric combustion (Arroyo et al. 2015).



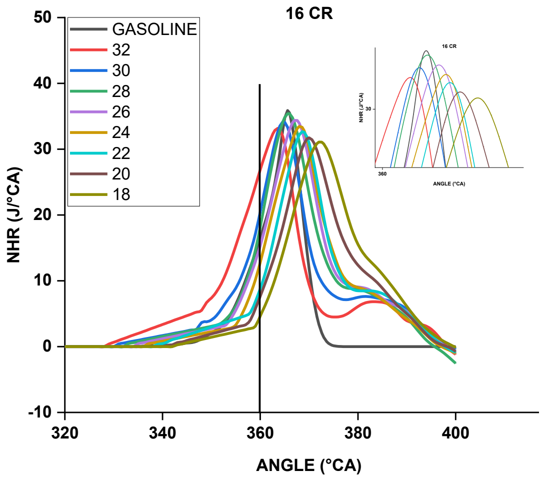


Figure 4.23 Variations in NHR with CR and Ignition Timing at 1400 rpm

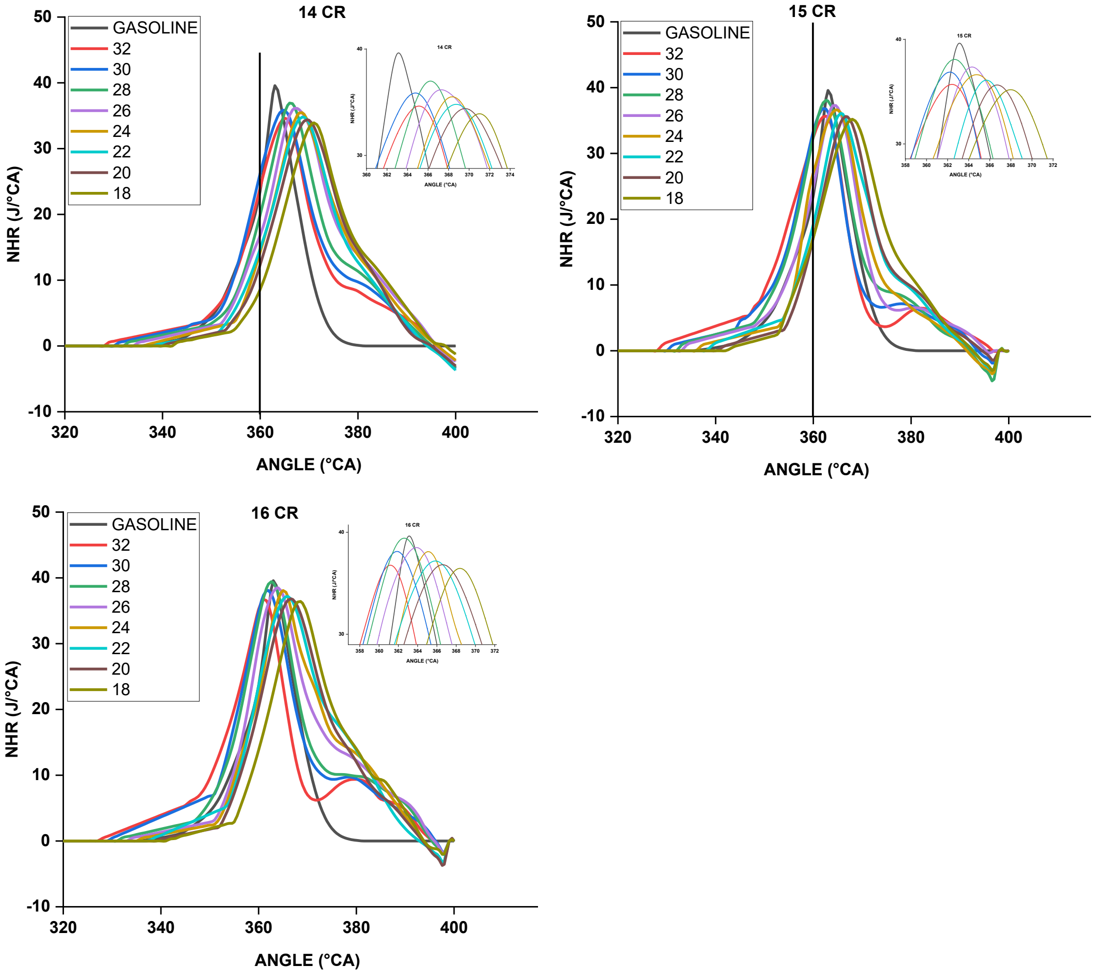


Figure 4.24 Variations in NHR with CR and Ignition Timing at 1800 rpm

4.3.6 Exhaust gas temperature

The temperature of the exhaust gases is determined by combustion characteristics such as the duration and location of combustion in relation to crank angle and engine speed. The increase in mean cylinder temperature, which causes an increase in exhaust gas temperature, is caused by the increased speed (Kilicarslan and Qatu 2017). Figure 4.25 shows the EGT variations at 1400 rpm and 1800 rpm when CR and ignition timing is varied. EGT is a measurement used to understand engine exhaust emissions and cylinder temperatures. EGT is also determined by engine speed because an increase in MGT results in insufficient time for engine cooling when engine speed is increased. At the end of the expansion stroke, the temperature rises, leading to an increase in EGT. To conserve energy, we must reduce the temperature of the exhaust gas. The effect of high-energy combustion with CR and speed intensifies, initially initiating combustion and increasing maximum temperature and EGT. The empirical studies indicate that EGT reduces due to the high RON of ammonia/hydrogen compared to gasoline, which promotes in-cylinder combustion and uses most of the combustion heat from the piston for work. When advancing ignition timing from 18ºCA to 32ºCA bTDC, the average drop in EGT is 4.3% at 1400 rpm and 5.5% at 1800 rpm for all CR. On the other hand, a low EGT indicates the most efficient utilization of engine-generated heat. Both the flame temperature and the exhaust temperature are decreased by the high latent heat of ammonia evaporation. High octane fuels accelerate in-cylinder combustion, thereby utilizing a greater portion of the heat for combustion and reducing EGT. Similarly,

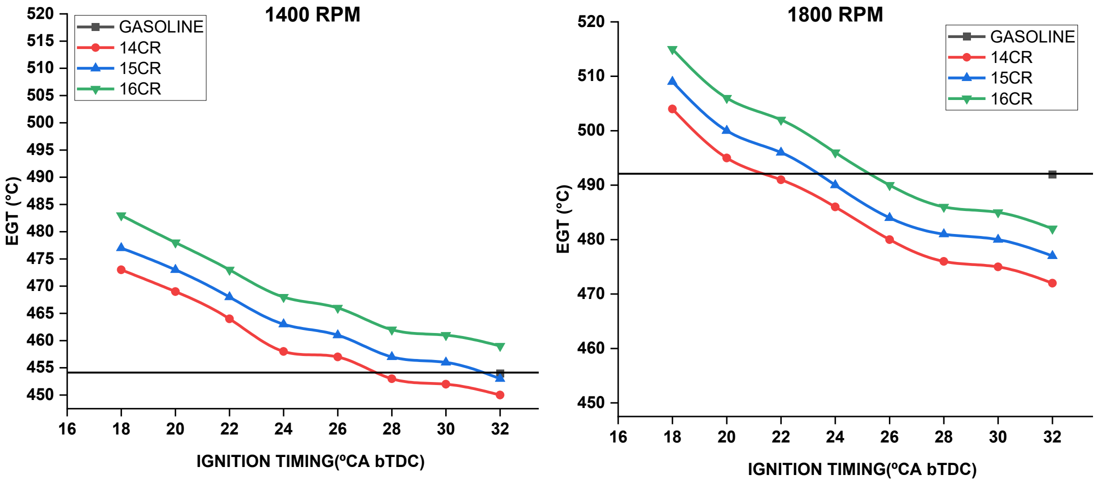


Figure 4.25 EGT Variations with CR and ignition timing at 1400&1800 rpm speeds

exhaust gas temperatures will fall if energy is to be conserved (Zareei and Kakaee 2013). Figure 4.25 shows that the EGT decreases as the ignition timing is advanced. The reason is that the heat release process happens earlier due to the spark timing advancement. Consequently, very little fuel is consumed as the piston moves away from the top dead centre. Therefore, exhaust loss decreases as spark timing is advanced (Su et al. 2017). Therefore, advancing the spark timing reduces EGT significantly. The addition of ammonia reduces EGT, indicating that ammonia has the ability to reduce exhaust loss (Chen et al. 2019b).

4.3.7 Oxides of nitrogen emissions

NOx is one of the major pollutants emitted by vehicles. It is essential to remember that several techniques prevent NOx generation during ammonia combustion by enhancing or lowering NO routes (Mohammadpour et al. 2022). NOx is created in the combustion chambers of internal combustion engines by the direct burning of atmospheric nitrogen or nitrogen in the fuel and oxygen. As shown in Figure 4.26, NOx is created by the interaction of ammonia/hydrogen under varying CR and ignition time at speeds of 1400 rpm and 1800 rpm. NOx emissions are typically caused by thermal NOx, prompt NOx, and fuel NOx. Nitrogen bonded to ammonia is the principal source of NOx, produced by fuel NOx. Maximum NOx was measured at 28ºCA bTDC due to higher temperature and pressure within the engine cylinder, leading to total ammonia combustion. In our research, the increase in NOx from 18 ºCA to 28 ºCA bTDC is 11.89% at 1400 rpm,14CR, 12.47% and 13.65% at 15CR and 16CR, and 12.27%, 12.87%, and 13.99% similarly at 1800 rpm. When the ignition timing is adjusted from 18 ºCA to 28 ºCA bTDC, NOx appears to increase with speed and CR, then declines. Although thermal NOx is the principal component, the fuel NOx of ammonia/hydrogen is more than thermal NOx. NOx generation by gasoline is lower than ammonia/hydrogen because ammonia/hydrogen has a combined effect of fuel NOx and thermal NOx. Fuel NOx is less susceptible to temperature and, more critically, is regulated by NH_3 oxidation-produced free radicals. Ammonia/hydrogen oxidation may generate more hydroxyl activities, increasing the ammonia oxidation rate and thus increasing NOx emissions. Moreover, NOx is enhanced with boost pressure because higher temperatures inside the cylinder result from more intense combustion.

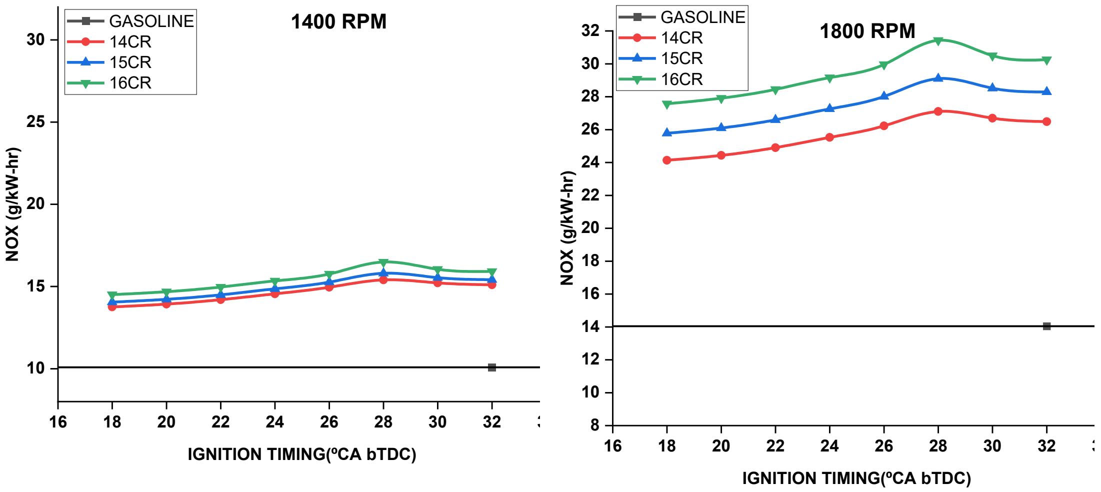


Figure 4.26 NO_x Variations with CR and ignition timing at 1400&1800 rpm speeds

4.4 Influence of EGR (Ammonia/Hydrogen)

The experimental results from stage II (ammonia/hydrogen) provide an optimal CR, blending ratio, and IT condition concerning better performance. CR15, at 21% hydrogen fraction, is observed to have the best performance, while IT of 28°CA bTDC has good performance. Hence, in stage II, experiments are conducted to control NO_x by EGR, and the illustration of the results with probable cause is provided below;

4.4.1 Brake power

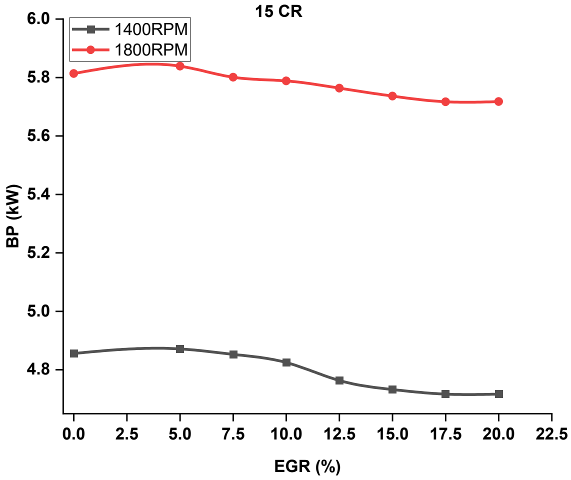


Figure 4.27 BP varies with EGR at 1400 and 1800 rpm

A decrease in brake power is observed after 5% EGR for both engine speeds and different EGR flow rates tested. The decrease in power is observed and increases EGR flow rates. Figure 4.27 depicts the variation in brake power with EGR flow rates. The highest reduction in power output can be noticed at 20% EGR. BP is primarily based on the total energy provided and the combustion rate; moreover, the fuel-air ratio and Cylinder pressure influence the combustion rate. Due to enhanced cylinder pressure, the combustion rate would also increase. However, EGR implementation decreases available oxygen. At low EGR, sufficient oxygen is available, which increases combustion speed; hence, BP increases at 5%EGR. While EGR is increased even further, large-scale dilution causes oxygen reduction and an increasing heterogeneity. Consequently, BP falls continuously. The rate of reduction becomes worse as EGR increases. After 5%EGR, the BP drop rate rises during both speeds due to EGR.

4.4.2 Brake thermal efficiency

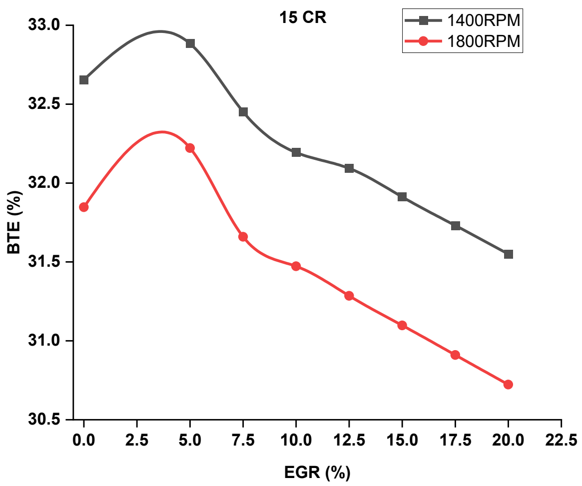


Figure 4.28 BTE varies with EGR at 1400 and 1800 rpm

At a high EGR rate, the BTE was reduced, as shown in Figure 4.28, because the combustion phase was far away from the top dead center during the expansion stroke, and the work capacity of a working fluid was reduced. However, EGR started to slow the combustion process even as the specific heat capacity of a working fluid continued to increase due to the addition of water vapor to the charge, resulting in a negative impact on BTE (Zhao et al. 2020). At an early EGR of 5%, stratification is replaced, improving combustion rate and enhancing BTE. The increase in BTE results from a decrease in pumping losses, a decrease in heat transfer, and a boost in the specific heat ratio. However, the situation keeps changing as EGR rates increase, which increases heterogeneity; consequently, BTE decreases rapidly with increasing EGR at both speeds.

4.4.3 Volumetric efficiency

Figure 4.29 shows volumetric efficiency, revealing the effect of EGR. Volumetric efficiency rapidly declines as high-pressure recirculated air replaces low-pressure intake air when EGR is applied. The in-cylinder volumetric efficiency declines with a drop in oxygen concentration as the EGR rate increases. The EGR leads to an increase in charge temperature and a decrease in charge density, which impacts the volumetric efficiency (Zhang et al. 2020). The drop rate is exponentially proportional to the EGR rate. The rate of decline varies with speed. With EGR, volumetric efficiency declines more rapidly as engine speed increases.

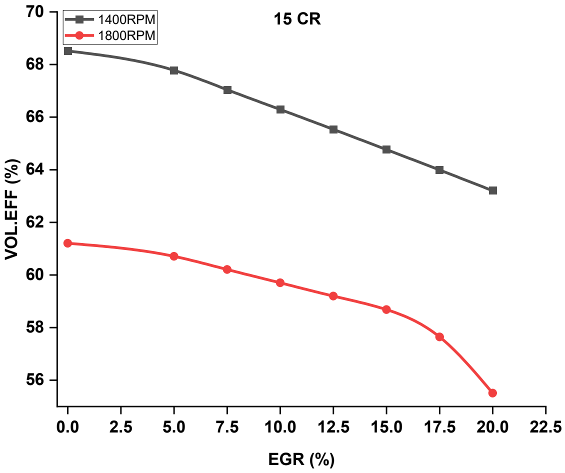


Figure 4.29 Volumetric efficiency varies with EGR at 1400 and 1800 rpm

4.4.4 Cylinder pressure

Figure 4.30 illustrates the impact of EGR on cylinder pressure at engine speeds of 1400 and 1800 rpm under CR15. Under air dilution conditions, as the EGR rate grew, the peak in-cylinder pressure steadily decreased, and the phase of peak in-cylinder pressure was delayed after 5%EGR. At 1800 rpm, whenever the EGR rate was 20%, the pressure dropped by 10.98%, and the phase of peak cylinder pressure was constantly retarded. In addition, EGR gas removed a portion of the fresh incoming air, reducing oxygen concentration sufficient to decrease the collision frequency of active species during the combustion process. Therefore, the combustion process was delayed, resulting in decreased cylinder pressure and a delayed combustion phase (Zhao et al. 2020). During periods of low EGR, high oxygen levels assist combustion by reducing sensible heat loss to cold air. Enhancing the combustion rate tends to boost the HRR; consequently, the CP starts increasing. In addition, extended combustion tends to enhance heat transfer to the water-cooled cylinder walls, resulting in the loss of useable energy. Consequently, after 5% EGR is observed, CP decreases.

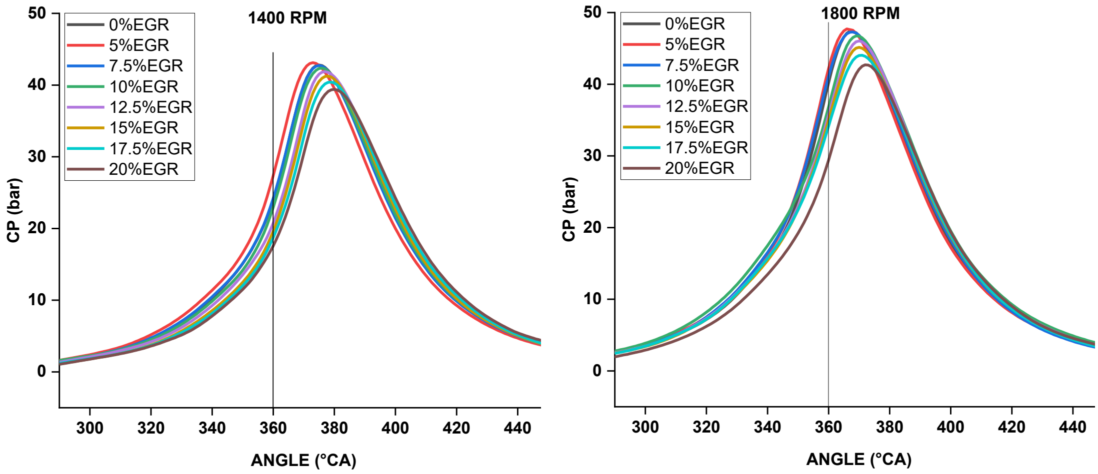


Figure 4.30 CP varies with EGR at 1400 and 1800 rpm

4.4.5 Net heat release rate

The impact of EGR on HRR is illustrated in Figure 4.31. After 5% EGR, the rate of heat release is evidently reduced. The addition of EGR negatively affected the flame's growth and propagation, and a higher EGR ratio could result in the delay and slowness of heat release in the cylinder (Xie et al. 2017). The delayed combustion process typically increases the heat released during the late combustion phase, thereby decreasing the conversion efficiency from in-cylinder combustion energy to useful engine work. Consequently, a larger mass ignites before TDC, resulting in a much more rapid increase in cylinder temperature and a rapid increase in HRR. A shorter combustion duration also causes the peak HRR to move closer to TDC. However, after 5%EGR of the curve exhibits a rapid decrease in HRR because a larger mass has already been consumed, and a small amount of fuel surrounded by primarily combusted gases faces slight difficulties in combustion. On the other hand, further enhancing EGR increases the amount of recirculates, which also reduces the oxygen reach of fuel and oxygen amount in the mixture; as a result, combustion elongates, which is accompanied by heat loss to the cylinder wall due to the long combustion duration, which further decreases HRR and delays the peak. As engine speed increases, volumetric efficiency decreases, allowing for improper engine breathing; as a result, further implementation of EGR significantly impacts flame propagation. Therefore, fuel consumption slows, and HRR decreases.

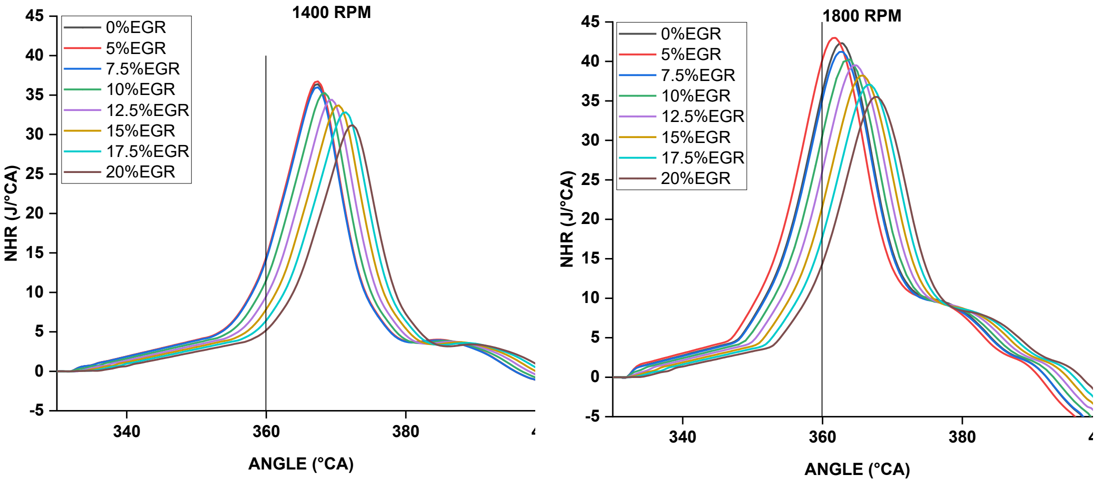


Figure 4.31 NHR varies with EGR at 1400 and 1800 rpm

4.4.6 Exhaust gas temperature

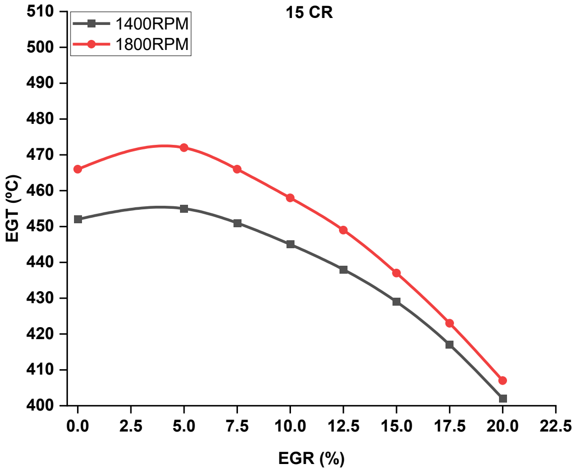


Figure 4.32 EGT varies with EGR at 1400 and 1800 rpm

As seen in Figure 4.32, higher EGR rates were associated with lower exhaust gas temperatures. Due to the improved specific heat ratio of the working fluid (Zhao et al. 2020), the installation of EGR lowered the combustion temperature, resulting in a lower exhaust temperature due to EGR's dilution effects. It appears that EGR is more successful in reducing NOx emissions. Because the exhaust temperatures fall with increasing EGR, it is safe to conclude that the combustion chamber temperatures also decrease, decreasing NOx generation.

4.4.7 Oxides of nitrogen emissions

High temperatures and an abundance of oxygen were required for NOx production. During EGR, the oxygen level in the combustion chamber is lowered, and the combustion temperature also decreases due to a working fluid's increased specific heat ratio (Zhao et al. 2020). After 5% EGR, NOx emissions exhibit a declining trend with increasing EGR ratios. This is because an increase in exhaust gas may dilute the oxygen in the cylinder and reduce the mixture's oxygen content. In addition, introducing exhaust gas can continuously increase the engine's specific heat capacity. As the EGR rate increased, NOx emissions reduced progressively, as shown in Figure 4.33. The mixture continues to reduce flame temperature and NOx emissions (Yu et al. 2021). The combustion process within the cylinder was slowed, and the amount of heat emitted decreased, which could reduce the peak and duration of high temperatures during combustion. With EGR, the cylinder's peak combustion temperature and oxygen concentration may be significantly reduced. Significant decrease potential for NOx emissions. Due to an increase in the amount of water vapor in the incoming air, the amount of energy required for the decomposition of water vapor increases, providing less energy for the thermal decomposition of O_2 and N_2 molecules. Therefore, raising the EGR rate reduces NOx formation by reducing NOx generation (Mardi K et al. 2014).

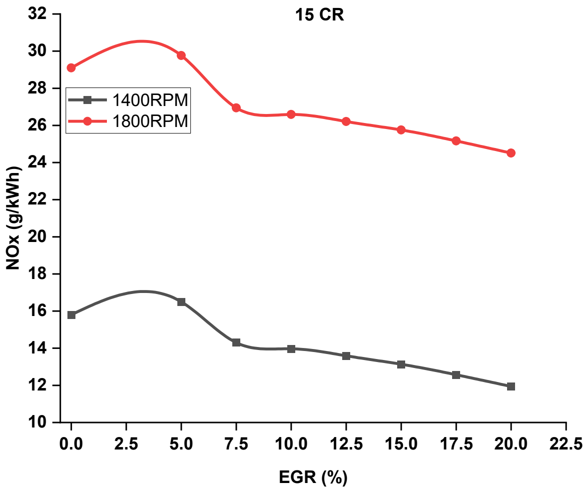


Figure 4.33 NOx varies with EGR at 1400 and 1800 rpm

CHAPTER 5

CONCLUSION

The main objective of this study is an experimental investigation of low-carbon and carbon-free fuels in a SI engine. Current research focuses on the effect of varying operating parameters, such as compression ratio, blends for methanol/LPG, and blends, compression ratio, IT, and EGR for ammonia/hydrogen, on the engine's overall performance, combustion stability, and emission characteristics.

When the operating parameters for methanol/LPG and ammonia/hydrogen blends are optimized, the performance, combustion, and emission characteristics are enhanced.

The following conclusions are made from the research.

Influence of CR and blending ratio (Methanol/LPG)

- Using LPG as a combustion promoter and energy enhancer compensates for methanol's drawbacks, such as difficulty starting and low heat content.
- Increasing compression ratio is also found to increase BP, BTE, and volumetric efficiency. When combined with LPG fraction, a net average increase of 51%, 21.2%, and 13% is observed in BP, BTE, and volumetric efficiency, respectively, when moving from 25% LPG fraction at CR12 to 45% LPG fraction at CR15.
- The EGT, P_{max}, and NHR_{max} are observed to rise with increasing LPG fractions and CR. From 25% LPG at CR12 to 45% LPG at CR15, the EGT, P_{max}, and NHR_{max} increase by a net average of 13%, 101%, and 27.8%, respectively.
- CO emissions drop with CR and increase with LPG fraction, whereas HC emissions decrease with both LPG fraction and CR, resembling disassociation reactions.
- CO_2 emissions grow with increasing LPG percentages and CR, while NOx emissions follow a similar trend but to a greater extent. It has been found that increasing LPG at greater CR increases NOx emissions.
- Based on the engine performance and emissions discussed above, the optimal compromise between engine performance and emissions was 35% to 40% LPG and 14 to 15 CR up to 1600 rpm. Hence, it is recommended that 14CR and 40% of the LPG fraction be added to methanol as an acceptable CR and mixing ratio.

- The performance evaluation and emissions show that the methanol/LPG mixture performs better than gasoline within the flammability limit.

Influence of CR and blending ratio (Ammonia/Hydrogen)

- Ammonia is a low-reaction chemical that requires the use of a combustion promoter in a SI engine.
- A moderate amount of hydrogen addition reduces ammonia's negative effects and improves performance; however, the reduction in vol limits the extent of the improvement. Ammonia/hydrogen has the highest BTE of 31.13%, while gasoline has a BTE of 27.77% and the volumetric efficiency decreased by 13.64%.
- Peak cylinder pressure and temperature are negatively affected by ammonia's low energy content and slow combustion speed, which is somewhat improved by raising CR and increasing the hydrogen fraction.
- When the CR (12-15) and hydrogen fraction (5-21%) are altered, the heat release rate at 1400 rpm and 1800 rpm increases by 28.84% and 36.3%, respectively.
- NOx emissions are intrinsic to the combustion of ammonia. However, as the hydrogen fraction increases, the NOx formation due to ammonia decreases while the NOx formation due to the peak temperature rise caused by hydrogen combustion increases significantly.
- The EGR and selective catalytic reduction (SCR) technique can significantly reduce excessive NOx emissions, a severe problem.
- Based on the engine performance discussed previously, the optimal balance between engine performance was 21% hydrogen fraction and 15 CR at 1400 rpm. As a result, it is advised that 21% of the hydrogen energy fraction be added to ammonia as an acceptable mixing ratio.

Influence of IT and CR (Ammonia/Hydrogen)

- Under different CR and ignition timing settings, the ammonia/hydrogen SI dual-fuel mode increased the combustion rate.
- The highest value of BP and BTE of an ammonia/hydrogen-fueled SI engine is increased by CR and ignition timing by 6.12 kW and 32.94%, respectively, whereas the highest value of BP and BTE in gasoline is 5.82 kW and 27.77%.

- The latent heat of vaporization of ammonia fuel is used more efficiently to decrease charge air temperature and boost volumetric efficiency. However, the volumetric efficiency was reduced to 9.5% due to hydrogen and increased speed.
- Adding hydrogen to ammonia enhances the combustion rate, resulting in a 10.35% rise in CP and a 9.53% increase in NHR, with a peak at 28ºCA bTDC, therefore, an increase in performance at 28ºCA bTDC. Therefore, 28ºCA bTDC is advised as the optimal spark timing for this VCR SI engine's ignition system.
- NOx emissions steadily increased with increasing CR and speed, reaching a maximum increase of 30.21% from 18ºCA bTDC to 28ºCA bTDC.

Influence of EGR (Ammonia/Hydrogen)

- A low EGR rate improves BP and BTE, whereas a high EGR rate drastically decreases performance.
- EGR raises the temperature in the incoming air, which causes expansion in the mixing unit, restricting a relatively large air intake and lowering η_{vol}.
- Increasing EGR decreases oxygen availability, resulting in prolonged combustion times. Consequently, HRR, CP, and EGT are initially intensified and lowered with EGR.
- EGR continually reduces particular NOx, except at 5% EGR. At high EGR, it controls the oxidation of nascent nitrogen and lowers T_{max}, reducing NOx to an extremely low level.
- The experiment results indicate that hydrogen can be employed as a combustion enhancer, creating a new benchmark for developing ammonia-fuelled engines.
- Methanol/LPG and ammonia/hydrogen are particularly attractive to future energy systems as low-carbon and carbon-free energy carriers for transportation.
- The investigation of the combination of methanol/LPG and ammonia/hydrogen is viewed as fulfilling both economic and environmental requirements.
- Methanol and ammonia are game-changing fuels for internal combustion engines as hydrogen carriers.

The following Limitations are made from the research.

- Due to the excessively lean mixture, it is difficult to operate the methanol-fueled engine under WOT conditions at maximum load, low speed, and low LPG fraction. A minimum LPG proportion of 25% must be maintained for sustained combustion.
- Below 5% hydrogen energy fraction, it is extremely difficult to ignite ammonia with a low rate of reactivity.
- At 18 and 20ºCA bTDC, the ammonia/hydrogen combustion efficiency is low. Starting the engine with less than 5% hydrogen energy fraction and a smaller CR at low speeds is difficult.
- Hydrogen/ammonia combustion increased NOx emissions as CR, ignition time, and engine speed increased, requiring exhaust after treatment.

5.1.Future Scope

Though there are satisfactory results obtained from the research, there are still more challenges to solve.

- ➢ An electronically monitored high-pressure methanol injection directly to the combustion chamber, variable ignition timing, and EGR technics are the most viable options for methanol/LPG dual fuels.
- ➢ In the ammonia/hydrogen direct injection technique, producing hydrogen onboard by dissociating ammonia and utilizing it in the engine can be a viable option. However, hybridization and fuel cell technology are potential alternatives.
- ➢ The introduction of EGR reduces NOx emissions but does not bring them close to zero. Therefore, various after-treatment methods, such as SCR, could effectively eliminate it.

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List of Publications based on PhD Research Work

[to be filled-in by the Research Scholar and to be enclosed with Synopsis submission Form]

S. No.	Authors (in the same order as in the paper. Underline the Research Scholar's name)	Title of the paper	Name of the Journal/ Conference/ Symposium, Vol., No., Pages	Month & Year of Publication	Category *
1.	Dinesh M.H., Jayashish Kumar Pandey, G.N. Kumar	Effect of parallel LPG fuelling in a methanol fuelled SI engine under variable compression ratio	Energy, Volume 239, 122134	September 2021	1
2.	Dinesh M.H., Jayashish Kumar Pandey, G.N. Kumar	Study of performance, combustion, and NOx emission behavior of an SI engine fueled with ammonia/hydrogen blends at various compression ratio	International Journal of Hydrogen Energy,47,25391-25403	June, 2022	1
3.	Dinesh M.H., G.N. Kumar	Effects of compression and mixing ratio on NH_3/H_2 fueled SI engine performance, combustion stability, and emission	Energy Conversion & Management-X,15,100269	July, 2022	1
4.	Dinesh M.H., G.N. Kumar	Experimental investigation of variable compression ratio and ignition timing effects on performance, combustion and NO_X emission of an ammonia/hydrogen-fuelled SI engine	Energy, EGY-S-22-07641	Under Review	2

5	Dinesh M.H., G.N. Kumar	Simulation of GDI Engine by Using CFD Modelling	Recent Advancements in Chemical, Energy and Environmental Engineering (RACEEE 2020), SSN College of Engineering, Chennai.	Feb 13-14, 2020	4

* Category: 1: Journal paper, full paper reviewed
2: Journal paper, Abstract reviewed
3: Conference/Symposium paper, full paper reviewed
4: Conference/Symposium paper, abstract reviewed
5: Others (including papers in Workshops, NITK Research Bulletins, Short notes etc.)
(If the paper has been accepted for publication but yet to be published, the supporting documents must be attached.)

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