PERFORMANCE, EMISSION AND COMBUSTION ANALYSIS OF A HYDROGEN ENRICHED METHANOL FUELED SI ENGINE

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

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June 2021

DECLARATION

I hereby declare that the Research Thesis entitled **"**Performance, Emission and Combustion analysis of a Hydrogen enriched methanol fueled SI 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 **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 other Universities or Institutes for the award of any degree.

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CERTIFICATE

This is to certify that the Research Thesis entitled **"Performance, Emission and Combustion analysis of a Hydrogen enriched Methanol fueled SI Engine"** submitted by **Mr. NUTHAN PRASAD B S (Register Number: 155008ME15F09)** 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.**

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Nuthanprasad BS

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ABSTRACT

The study of potentially high rated alternative fuel (Methanol) for the IC engines is an exciting topic in the recent research advancement. The characteristics of methanol are distinct yet promising in terms of combustion, renewability, and sustainability. The experimental trials were conducted in wide-open throttle conditions (WOT) for different speeds ranging from 1200 rpm to 1800 rpm at an interval of 200 on a single-cylinder four-stroke variable compression ratio (VCR) SI engine. Initially, the quantitative analysis of different methanol/gasoline blends ratios was conducted to study the engine characteristics. Later, a quantitative analysis of the M50 fuel blend was done for different ignition timing (18° BTDC - 24° BTDC) and compression ratio (8, 9 & 10). The study of high fraction methanol blends fueled in the standard SI engine model provides the convenience of the use of methanol in IC engines with small operating changes. It also guides the researchers to explore the effect of change of operating parameters with a small modification to the existing engine that can operate with neat methanol.

The present investigation's main objective is to study the performance, combustion, and emission characteristics of methanol fueled SI engine and further enrich with hydrogen fuel. The experimentation was conducted for four different compression ratios (11,12,13 and 14) at a different speed range of 1400 rpm to 1800 rpm, and the engine operated with WOT condition. The experimental data reveal that SI engine fuelled with neat methanol works smoothly and showed good results with compression ratio CR14. Further, the experiments were conducted by fixing the Compression ratio to CR14, and the ignition timing was optimized for a better outcome. Hence trials were conducted for different ignition timings (18° BTDC to 26° BTDC with a 2° crank angle difference). The performance evaluation suggests that neat methanol showed a difference of nearly 30 % improvement in BTE with CR14 and 8% further enhancement with the ignition timing of 20° BTDC. Methanol with lower energy content has a lower power output than gasoline and susceptible to an increase in specific fuel consumption. In this present case, neat methanol is operated with a higher compression ratio, which has a big impact on increased power output compared to lower CR (an increase of BP by 21% with CR14 compared to CR11). Undoubtedly, the low carbon composition of methanol is expected

to produce fewer oxides of carbon, HC. In addition to this, reduced in-cylinder temperature, directly reflecting on the reduction of NO_x emissions.

The effect of enriching methanol-fueled SI engine with hydrogen gas is studied in the present work. In the experiments for a different set of trials, including hydrogen enrichment ranging between 5% to 20% in volume with a 2.5% increment, the engine is operated with wide-open throttle (WOT) condition for different speeds. The percentage increase in performance is between 20-30%, and an increase in hydrogen beyond 12.5% would affect the volumetric efficiency, and thus performance declines after that. The exhaust emissions have a huge impact on hydrogen enrichment; CO, HC, and CO_2 emission are reduced by 30-40%, whereas an increase in cylinder temperature due to rapid combustion slightly increases the NO_x emission.

Finally, this research project aimed to study the feasible techniques related to the use of methanol in the SI engine and ensure smooth working capability without compromising efficiency and exhaust emission. The intention was also to focus on new combustion engine technology concepts, which can be co-developed with alternative renewable fuels. It was a conscious effort to work towards securing energy resources and provide a viable option for sustainable transportation technology. It also suggests the creation of a huge opportunity in the field of production and supply of sustainable alternative fuel.

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NOMENCLATURE

M_x	Where, x= 10%-50% methanol by volume
BTDC	before Top Dead Centre
BSFC	Brake Specific Fuel Consumption
BSEC	Brake Specific Energy Consumption
BTE	Brake Thermal Efficiency
BP	Brake Power
NO_x	Oxides of Nitrogen
CO	Carbon monoxide
CO_2	Carbon dioxide
HC	Hydrocarbon
PE	Performance Electronics
DAQ	Data Acquisition system
ECU	Electronic Control Unit
SI	Spark Ignition
VCR	Variable Compression Ratio
EPFI	Electronic Port Fuel Injector
ADC	Analog to Digital Converter
DME	Dimethyl ether
WOT	Wide-open Throttle
RGF	Residual Gas Fraction
RWGSR	Reverse Water Gas Shift Reaction
MTBE	Methyl tert-butyl ether
CPS	Crank Position Sensor
TPS	Throttle Position Sensor
CDI	Capacitor-Discharge Ignition
CI	Compression-Ignition

SYMBOLS

$\dot{v}_{H_2}$	the volume flow rate of hydrogen in l/min
$\dot{m}_{M_{50}}$	the mass flow rate of M_{50} fuel in kg/hr
ρ_{H_2}	the density of hydrogen in kg/m^3
x_{H_2}	energy fraction of hydrogen
$(\bar{\bar{x}})$	mean values of parameters
σ_i	standard deviation
$\in_{H_2}$	The energy density of hydrogen
$\in_M$	The energy density of Methanol

CHAPTER 1
INTRODUCTION

This chapter highlights, utilization of methanol fuel as transportation fuel based on its physical and chemical properties in IC engine combustion. It also highlights the country's economic scenario and government norms to introduce methanol into the transport section. The review of methanol production and utilization are highlighted in this chapter. Hydrogen having the best combustion characteristics is used as a supplementary fuel to the methanol is also summarized.

1.1 Background

Fossil fuel dominance in global energy systems is eyeing dire need of attention soon. The fossil energy source was a fundamental commodity that bought a big revolution in the industrial and the technological development process, along with social and economic status. However, such developments have a huge negative impact on the environment; these hydrocarbon fuels are a major emitter of carbon dioxide and greenhouse gases. Developed countries are finding a balance with energy requirement by reducing the dependency on fossil fuel and move towards low carbon alternative sources of energy. In 2015 world leaders came together to address the global environmental concerns by adopting a legally bound treaty called 'Paris Agreement' (UN Framework Convention on Climate Change (UNFCCC)). The agreement aimed to drastically reduce global greenhouse gas emissions in an attempt to restrict the rise in global temperatures to 2 degrees Celsius. India is the only G20 nation on track to fulfil what was promised in 2015 under the Paris Agreement on climate change.

The energy sources such as wind energy, solar energy, nuclear energy, hydroelectric energy, and etc., have hardly been proved as the sustainable source to replace fossil-based fuels. The most viable alternative fuel found to be the methanol fuel, which is offering, the right balance between fuel economy and decarbonize the surrounding. Figure 1.1 shown below is the pictorial representation of balancing between harmful pollutants and the socio-economical environment.

The utilization of methanol fuel was first discovered in 1823; methanol is a colorless, odorless, slightly inflammable liquid, and it is also called methyl alcohol or wood alcohol. Methanol can be produced from biomass, which contains carbon contents. It is a widely used chemical compound from 100 years to make solvents, plastics, plywood, and paint.

It was a German-based company BASF in 1923; developed a catalytic process to produce methanol on a large scale for commercial use (Sheldon 2017). Soon after, coal-based methanol synthesis is becoming popular, and researchers started exploring methanol as a source for energy independence.

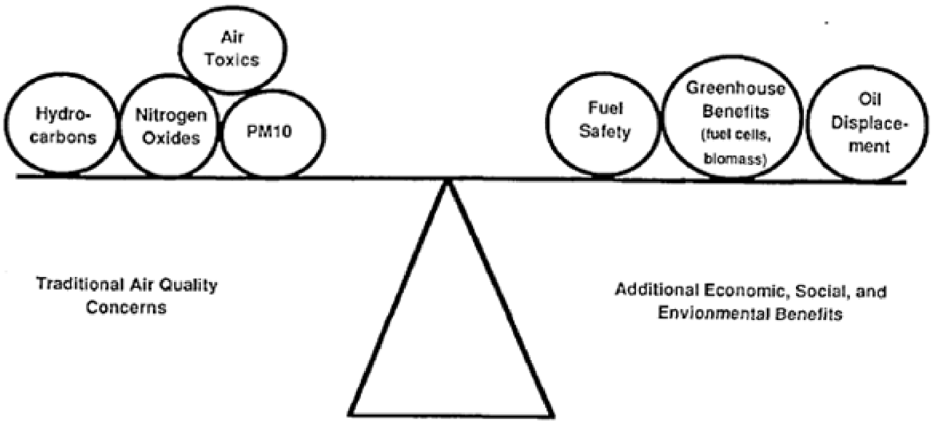


Figure 1.1 Methanol fuel use to balance concern about the control of traditional air pollutants. (Source: Acurex Environmental)

The promotion of worldwide utilization of methanol in vehicles started in the late 1970s; it was the first oil crisis in 1973, which paved the way for methanol to evolve as an alternative fuel to satisfy the demand for transportation fuel (Reed and Lerner 1973). Methanol was initially used as an octane booster, and it slowly gained interest when the United States passed a bill for Clean Air Act Amendment (1990). It paved the way towards using high octane, oxygenated fuels such as Methanol, as the best alternative fuel for gasoline. M85 engines hit high in the US market in 1997 (Bechtold 2007). However, refiners came up with reformed unleaded gasoline and after-treatment catalysts to counter the emission crisis. In the backdrop, global oil prices reduced and thus hindered the greater plans for deploying methanol for commercially large-scale usage in the field of transport.

The production of methanol from the gasification process is relatively small compared to the production of gasoline and diesel. The major outcome in methanol production was the recovery of CO_2 from the atmosphere using the Carbon Neutral cycle (Olah et al. 2006). At present, China dominated the production and utilization of methanol. The abundant coal resources and the mastery over the low-cost production technology of methanol from coal(Yao et al. 2016) have succeeded in China to have a stronghold on the utilization of methanol for domestic purposes. Analyzing the production, utilization, and transportation statistical data of methanol in China, and China is said to be the largest user of methanol since from 2006 (Su et al. 2013). Su L. W et al. (2013) reported that, roughly 8% of the methanol fuel used in the Chinese transportation system.

1.2 Methanol Economy

The estimated requirement of Petrol and diesel in India are 28.3 and 83.5 million tons per year, respectively; currently, India is the 3rd largest energy consumer in the world. The situation has arisen where the developed countries should take measures on air pollution along with energy demand. Figure 1.2 shows India's growing demand for crude oil products. Indian consumption growth rate is expected to outpace China in the coming years. India being the third highest emitter of carbon dioxide from energy sources, is planning to impose strict emission norms and set a goal to reduce import bills of crude oil by 10% before 2022.

The double-digit demand growth in the methanol market has put up a stiff challenge for the supply regiment. A technical research report titled "India Methanol Market Study, 2011 – 2025" predicts, the methanol market in India is estimated to grow at a Compound Annual Growth Rate (CAGR) of 7% over an expected period.

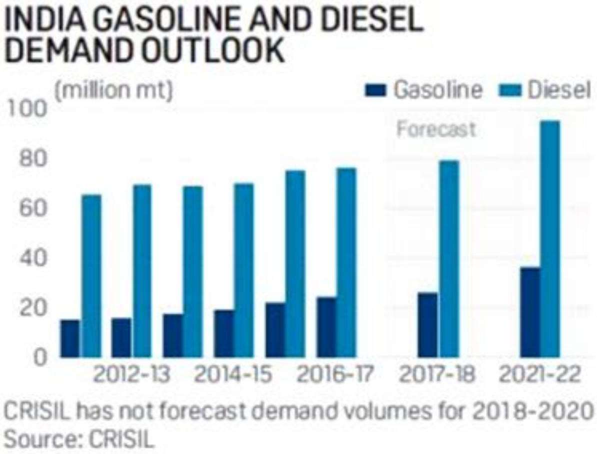


Figure 1.2 India crude oil product demand (source: CRISIL)

The major demand for methanol is for formaldehyde manufacturing coupled with other chemical compounds such as acetic acid, MTBE, etc. India is still at an early stage of methanol production and usage, but it has massive potential considering coal reserves and other available resources. Despite having a production facility, India imports methanol to meet its demand; at present, 90% of the market is met through imports.

1.3 Necessity of Methanol

Prices of fossil fuel have never been more robust, driven by the economic development of surrounding countries, upon which our energy requirement is dependent. There is an urgent need for maintaining energy security over the exercise of price control. Some major environmental and social issues are associated with fossil fuel use, which causes global warming and undesired health hazards in society. Hence, considering these factors of concern, methanol is the best example for an alternative energy source. The scope of research for the inclusion of methanol in the transportation section draws major attention.

The governing bodies are proposing a universal strategic plan for a sustainable energy system by using methanol as an energy carrier. The availability and the scope of large-scale production from the different energy sources include solar, wind, and biomass, which are sources of renewable fuel. Utilization of methanol is increased in transport and power generation due to advanced technology for production and storage. Because of this the minimal dependence on non-renewable fossil fuels and diversify energy supplies. At present, research advancement is working towards some of the technical challenges that exist in the usage of methanol. It can be successfully burned in conventional IC engines with minimal design changes.

The feasibility of methanol as fuel in engine's application is dependent on the different aspects of sustainability, economical, and satisfactory solution to a number of operative limitations. The challenges are related to usage, technical development, storage, transport, and chemical characteristics of methanol as a fuel.

The growing fuel cell market has driven attention by methanol and hydrogen, two sources with high energy density. Methanol fuel cell is also a potentially key technological development in supporting climate change and achieving energy security goals in the transport, industry, and power sector. Methanol, as a hydrogen carrier, has a different role to play in the future. In association with methanol fuel, hydrogen fuel cell technology can reduce the operational flexibility to achieve dependency on fossil fuel in the transport sector, integrate with one or more renewable energy share to power the system.

Many technologies are still in the developing stages and yet to make a mark in the commercial sector. The high production cost and market requirements are a challenging task for fuel cell technology. Governments are encouraging by providing funding to research and development of a fuel cell-based transportation system, and many researchers are working towards the development of efficient fuel system.

1.4 Production of Methanol

Methanol production technologies have changed over the years, from simple destructive distillation of wood to commercial-grade industrial synthesis. Methanol synthesis is done from carbon-based feedstocks, such as coal, natural gas, biomass, or it can also be produced from a carbon-neutral cycle or also called as CO_2 hydrogenation. The energy conversion efficiency of methanol production using the following methods

a) Natural gas/Syngas 60-65 percent

b) Coal Gasification 47-52 percent

c) Biomass synthesis 42-52 percent

The production yield is higher than the process followed to extract gasoline and diesel (Fischer-Tropsch method). The estimated cost of methanol produced from coal synthesis is nearly the same as gasoline in the US and Germany; it can further go down with mass production.

1.4.1 Natural Gas or Syn-Gas as a feedstock of Methanol Production

Most of the industrial supply of methanol is extracted from natural gas. The extraction process follows three necessary steps:

- Production of synthesis gas
- Syngas conversion to crude methanol
- Distillation process

Figure 1.3 shown here is the schematic flow chart of the process involved during the conversion of Natural gas into methanol. The catalytic reforming (steam reforming and thermal reforming) of natural gas to produce syngas (H_2, CO, and CO_2) is the first step in the methanol synthesis and reaction 1 and 2(shown below). However, syngas can also be processed by partial oxidation of natural gas, as shown in reaction 3 for other carbon-based feedstocks (coal, biogas).

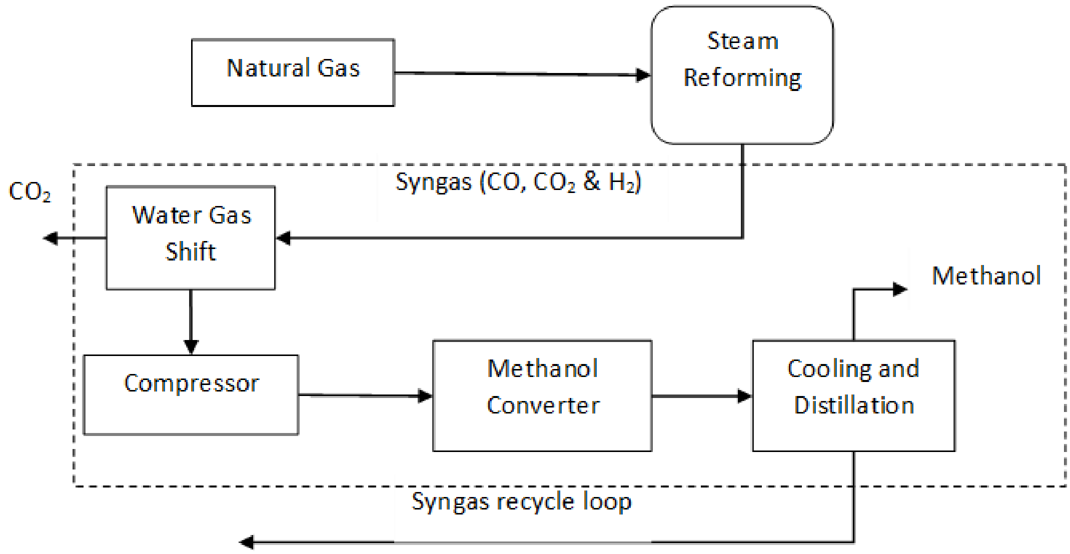


Figure 1.3 Synthesis of methanol from natural gas

Steam reforming: $CH_4 + H_2O \leftrightarrow CO + 3H_2$ (1)

Auto thermal reforming: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ (2)

Partial oxidation: $CH_4 + 1/4\ 2O_2 \rightarrow CO + 2H_2$ (3)

Methanol synthesis from the syngas involves reverse water gas shift reaction (RWGSR) to separate CO_2 from CO and H_2. The CO_2 removed can also be utilized to produce methanol as followed in reaction 5

RWGSR: $CO + H_2O \rightarrow CO_2 + H_2$ (4)

Synthesis: $2H_2 + CO \rightarrow CH_3OH$

Or Hydrogenation of carbon dioxide:

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad (5)$$

1.4.2 Coal and Biomass as Feedstocks for Methanol Synthesis

The process involving the extraction of methanol from coal is shown in Figure 1.4. Coal one of the biggest energy resources in the world, and presently appears to be the best choice of feedstock. The chemical synthesis of coal to produce methanol, the process followed, is very similar to the one related to the extraction process from natural gas. The final three stages of methanol synthesis, which involve syngas production, crude methanol extraction, and distillation (purification), are almost the same in all other feedstocks.

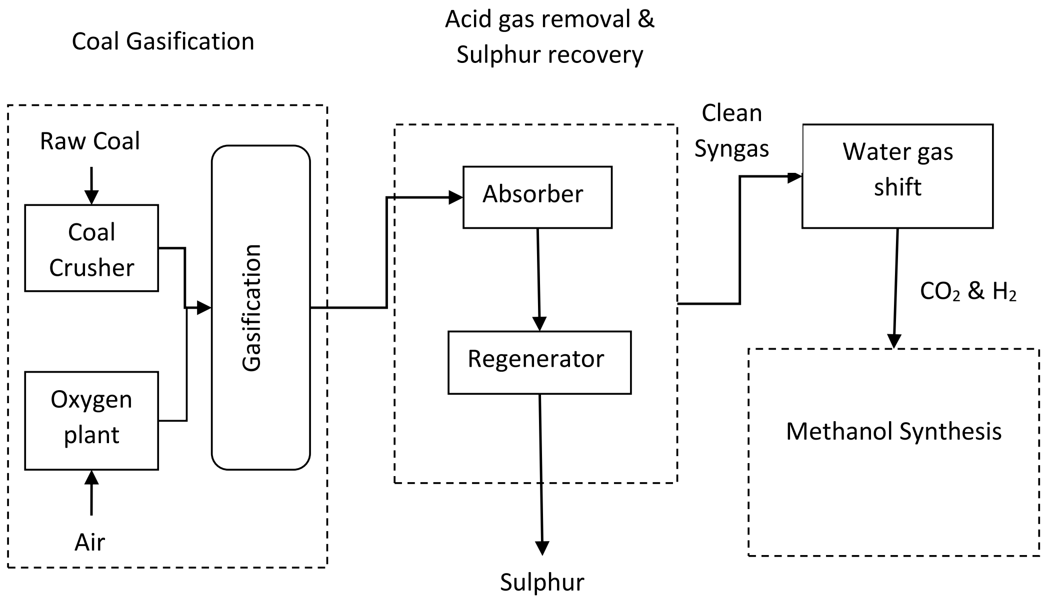


Figure 1.4 Synthesis of methanol from coal and biomass

The most commonly used procedures to convert coal into liquid methanol are via gasification and pyrolysis (Swain et al. 2011). Based on technical and economic performance, the study says, gasification of biomass or coal for the synthesis of methanol is an economical method for large-scale production (Shabangu et al. 2014).

The process begins with Brakeing up of large cellulosic and lignin molecules in the presence of an oxidizing agent (air/oxygen, steam) at temperatures ranging from 800°C to 1000°C; the transformed gaseous products includes biogas (CH_4, CO_2), syngas (CO, CO_2, H_2), lighter hydrocarbons, char, and impurities. The obtained hot syngas is cooled to below 300°C using a heat exchanger. It then passes through a condenser to remove moisture and particulates while reducing the syngas temperature further below 100°C. The product syngas is passed to acid gas removal and the sulfur recovery stage. Finally, clean syngas suitable for methanol synthesis is processed in the water gas shift column to regulate CO and H_2 ratio. Following these procedures, methanol conversion and refining is performed.

1.4.3 Methanol Synthesis from CO_2

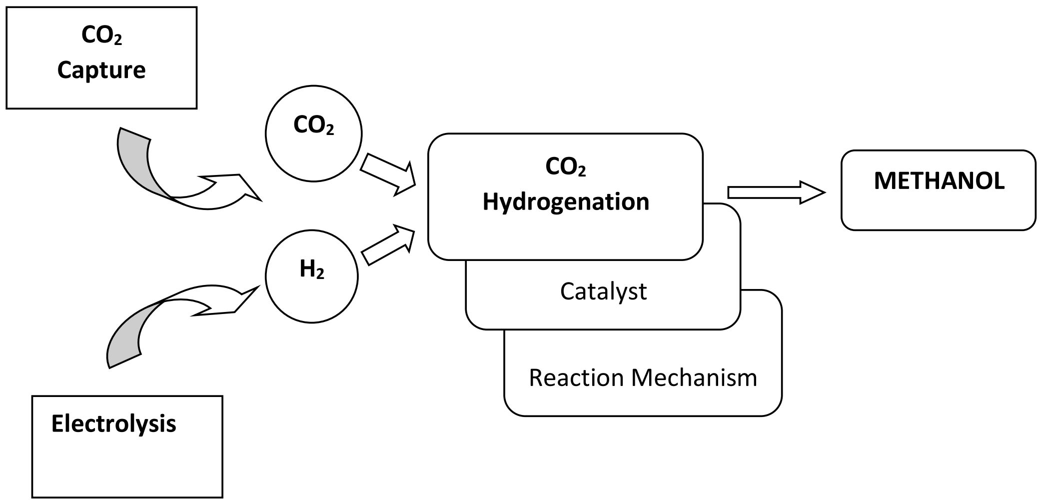


Figure 1.5 Synthesis of methanol from CO_2

Methanol is a principal organic compound, which is used in the chemical and energy industries, is of chief requirement. With the growing demand, the methanol production capacity installed worldwide is estimated to be 200MT by 2025. Conversion of CO_2 to methanol is considered to be a useful method of CO_2 utilization, where there is an urgent need to recycle carbon and reduce the emission of CO_2. Besides, CO_2 availability in abundance is a big feedstock for the production of chemicals, fuels, and raw materials. Figure 1.5 shows the process cycle involved with the synthesis of methanol from CO_2. The catalytic regenerative process, which involves CO_2 and H_2 to produce methanol, is one of the old methods. Olah et al. (Olah 2005; Olah et al. 2009) conducted a study and proposed several methods of methanol production and its derivatives and its uses.

Methanol synthesis from CO_2 is an advantageous approach owing to sustainable development. A non-fossil energy source that emphasis renewable, carbon-neutral and which are utilized for storage of energy, production of transportation fuels, and used as a feedstock for producing secondary chemical compounds. The synthesis of methanol from CO_2 and H_2 comprises of two-step reaction (Dang et al. 2019).

Methanol Synthesis:

$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$

Reverse water gas shift (RWGS) method:

$CO_2 + H_2 \rightarrow CO + H_2O$

In this process, carbon dioxide is readily available in the surrounding atmosphere; the required hydrogen is obtained from the hydrolysis of water. The hydrogenation of methanol is done by either using catalytic regenerative conversion with hydrogen or by the electrochemical reduction process.

1.5 Physical and chemical properties of methanol relevant to engines

Methanol contains only half the energy per gallon of gasoline but has a very high octane rating. Increased compression ratios could yield 5 to 20 percent more power, Gong, C et al. (2015). When methanol is used as a gasoline additive, antiknock compound, and fuel extender, it becomes economical with very positive results, especially from the emissions standpoint. It contains zero sulfur, thereby reducing tailpipe acids significantly. The major drawback of methanol as a fuel is its cost and the volatility of pricing. While methanol prices have been highly volatile in the past, there is little prospect for it to become price competitive with conventional fuels unless world oil prices increase greatly. The low energy density of methanol means that a large amount (roughly twice the mass of gasoline) is required to achieve the same power output.

Similarly, higher latent heat of vaporization increases the ignition delay; hence special attention is needed to design intake manifolds and ignition systems for cold start procedures. Otto-cycle engines using pure methanol (M100) become nearly impossible to start below 5ºC without special pilot fuels or supplementary heating techniques. Thanks to recent developments, various engine and vehicle modifications to the problems have been reviewed and assessed based upon selected criteria. In general, the most attractive solutions involve fuel modifications as well as fuel system design and material changes. One such fuel modification consists of the enhancement of hydro-carbons to neat methanol. Table 1.1 shows the physical and chemical properties of methanol, gasoline, and hydrogen.

Table 1.1 The properties of Methanol, Gasoline, and Hydrogen (Verhelst, Turner, Sileghem, & Vancoillie, 2019; Zhen & Wang, 2015).

Fuel Property	**Methanol**	**Gasoline**	**Hydrogen**
Formula	CH_3OH	C_{5-12}	H_2
Molecular Weight	32	95-120	2.02
Oxygen content	50%	0	0
Density (kg/l)	0.79	0.77	0.00008
Stoichiometric air/fuel ratio (kg/kg)	6.5	14.6	34.2
Low calorific value (MJ/Kg)	19.66	44.5	120
High calorific value (MJ/Kg)	22.3	46.6	142
Volumetric energy content (MJ/l)	15.9	33.18	0.0096
Boiling Point (^{0} C)	64.8	30-220	-253
Freezing Point (^{0}C)	-98	-57	-403
Flash Point (^{0} C)	11	-45	-
Auto- Ignition Temperature (^{0} C)	738	465-743	858
Research Octane number	109	80-98	130+
Motor Octane number	88.6	81-84	NA
Cetane number	3	0-10	-
Flammability limit	6.7-36	1.47-7.6	4-75
Specific heat (20 ^{0} C) (kJ/kg K)	2.55	2.3	14.31
Viscosity (20 ^{0}C) (CP)	0.6	0.29	-
Heat of Vaporization (kJ/kg)	1100	310	461
Adiabatic flame temperature (^{0} C)	2143	~2275	2390

The following conclusions are drawn regarding methanol as an automotive fuel

Benefits

1. High octane number fuel elevates the knock resistance. It helps in achieving higher power and efficiency by operating on a high compression ratio, optimal ignition timing, and engine downsizing.
2. Higher volatility, resulting in good atomization of fuel and better air-fuel mixture formation during the combustion
3. Higher Latent heat of vaporization, resulting in a temperature drop across the inlet manifold and thereby increasing the volumetric efficiency
4. Low carbon fuel gives clean combustion (no soot formation)
5. Large flammability limits and high flame speed capabilities, aides for lean mixture combustion, also results for good performance and lower exhaust emission.
6. Lower NOx formation due to low combustion temperature
7. Easy load control operations by varying mixture composition or varying the EGR percentage

Demerits

1. Corrosive and miscible with water
2. The lower energy density (half of the gasoline)
3. Cold start problems
4. Poor self-ignition properties (long ignition delay)
5. Poor miscibility with mineral fuels (especially with diesel oil) in the presence of water
6. Difficult starting of the cold engine
7. Corrosion and chemical degradation of materials

1.6 Hydrogen Enrichment

This section of the thesis includes a scope of hydrogen employment in an IC engine, where hydrogen can burn directly or mostly used as an enrichment agent to the primary fuel. The study conducted with alternative fuels and hydrogen is more promising for the near future. However, results concerning combustion, performance, and emission was impressive but economical, storage and safety prospect of hydrogen in the automotive sector is still a matter of concern (Verhelst and Wallner 2009). The energy demand is expected to increase by 50 percent globally, where India has a significant share in energy demand. The state-of-the-art production, manufacturing, and transport sector have a high energy demand. The country's economic growth rate is directly related to energy consumption per head of the total population.

Hydrogen is one of the prospective sources of energy with high energy density per unit mass. It is available in abundance with the combination of other compounds; hence it is also called a secondary energy source. The earth's surface is engulfed with water and air, comprising of hydrogen in abundance. Hydrogen consists of one proton and one electron; it is a fundamental building block for the formation of other elements. A diatomic molecule, which is chemically active by forming molecules such as water, combining with oxygen and carbon, forms a series of hydrocarbon chains with varying molecular structures. Hydrogen is perhaps the perfect fuel given its infinite source capacity and a clean-burning characteristic compared to various alternatives considered today and thus emerging as a promising fuel source for the future. The Hydrogen economy study has gained interest among the large population of environmentalists and researchers from the energy sector. The research communities are promoting hydrogen as an alternative energy source via publications, research interactions, symposiums, and exhibitions.

Hydrogen production is relatively simple as it is produced from the electrolytic process of splitting water into oxygen and hydrogen gas. Hydrogen is one of the clean energy sources available, and it is having suitable combustion characteristics for IC engine applications. When exhaust emission is concerned, it burns with the lowest percentage of oxides of carbon and hydrocarbon level. A fuel with good burning characteristics includes a broad range of flammability limits, ignition energy requirement should be minimum, higher energy content, and increased burning velocity. Hydrogen here satisfies all the combustion requirements, and it is considered a potential renewable energy source for the future. Hydrogen operating at high temperatures might be a bit of concern due to an increase in NO_x at the exhaust. Working hydrogen at lean mixture was a temporary solution to control NO_x; recent research on exhaust treatment has found a way to minimize the NO_x emission by introducing catalytic reactors at the exhaust.

The characteristic features of hydrogen as a combustible fuel are presented in this section. Some of the essential physical and chemical properties of hydrogen, gasoline, and methanol (Das 1990; Krishnan Unni et al. 2017; Verhelst et al. 2019) are listed in Table 1.2.

Table 1.2 Characteristic properties of three different fuels

Property	**Hydrogen**	**Methanol**	**Gasoline**	**Effect on engine**
Limits of flammability in air, vol%	4.0 to 75.0	6.7 to 36	1.0 to 7.6	The engine can run on a lean mixture
Stoichiometric volume fraction (in air)	0.30	0.12	0.02	Volumetric efficiency
Minimum energy for ignition in air, mJ	0.02	0.14	0.25	Operate with low residual energy
Autoignition temperature, K	858	738	465- 743	Knock resistance
The adiabatic flame temperature in air, K	2390	2143	~2275	Related to the completion of the combustion process
Burning velocity in NTP air, cm s^{-2}	325	37 to 45	37 to 43	Ideal combustion
Quenching gap in NTP air, cm	0.064	0.203	0.2	Tendency of backfire
Diffusivity in air, $cm^2\ s^{-1}$	0.63	0.2	0.08	Ability to form uniform air/fuel mixture
Limits of flammability (equivalence ratio)	0.1 to 7.1	0.55 to 4.32	0.62 to 3.89	

All the above-listed fuel properties signify hydrogen combustion characteristics, which can be used as a supplementary fuel or shows the potential alternative fuel for IC engines. Also, with no carbon atom presence, hydrogen enrichment has the advantage of low carbon emission with a methanol-fueled engine.

With more emphasis on hydrogen's good fuel characteristics, there is always a certain drawback associated with the hydrogen. There is a continuous effort carried out to address these negative aspects of the hydrogen. Some of the less favorable properties associated with hydrogen are listed here:

- Hydrogen is a gaseous fuel which is having the lowest density. Hence it has to be stored by compressing it to a liquid state under immense pressure, and also temperature has to kept lower to ensure the effectiveness as an energy source.
- Hydrogen engines operate with lean mixtures and lower power output due to it's lower heat content per unit volume stored at liquid state
- Odorless, colorless flame of hydrogen is always challenging to detect. Hydrogen is highly flammable, and it is associated with backfire at the intake manifold, creates an area of concern for use in IC engines.
- Engine operating with hydrogen produces high temperature and pressure inside the combustion chamber; this will leads to more nitrogen oxides.

The scope of study with respect to hydrogen fuel is wide, where the previous studies related to the use of hydrogen gas in IC engines have focused on blending hydrogen with gasoline or diesel and check for the characteristic improvement(Elsemary et al. 2016; Şöhret et al. 2019; Wang et al. 2014; Yu et al. 2019). Similarly, hydrogen enhancement for the alternative fuels such as methanol, ethanol, and other bio-oil sources are studied and documented in the many open source journal paper; surprisingly, researchers found a great deal of improvement with the combustion, performance, and reduced emissions (Gong, Li, Yi, et al. 2019; Zhang et al. 2014, 2016). Hung et.al. (Hu et al. 2009; J. Wang et al. 2010) suggested the correlation between burning velocity and radical concentration, where hydrogen addition enhances the chemical reaction due to increase in H, O and OF radical mole fractions(Huang et al. 2006). However, our focus is mainly on the utilization of methanol and hydrogen combination fuel characteristics. There are few papers which focuses on these methanol/hydrogen fuel blends; papers related to study using different methodology and different operating parameters are available in the open source. Hydrogen enrichment to methanol has shown a good improvement with BSFC and increased BP (He et al. 2018; Kak et al. 2015; Yilmaz and Taştan 2018). Gong C. (Gong et al. 2020) studied the hydrogen assisted combustion for medium compression ratio DISI methanol engine; their results shows the improvement over combustion stability and scope of increasing the lean burn limit to excess air ratio. Further, numerical study of DISI methanol engine with hydrogen addition has shown an improvement in combustion characteristics and emission of CO and unregulated gases have reduced substantially(Gong, Li, et al. 2016). The enrichments of hydrogen to gaseous fuels were also studied, and interesting results were observed and documented by several researchers (Albayrak 2012; Cattelan and Wallace 2010; Ma et al. 2010).

1.7 Thesis outline

The present research work includes the details of an experimental investigation carried out to evaluate the performance, combustion, and emission characteristics of the SI engine tested with gasoline/methanol blend and neat methanol. Finally, a small fraction of hydrogen was added to neat methanol operation for enhanced results. The experimental trials are divided into three parts. The first part involves the study of fuelling different methanol/gasoline blends. The second part consists of working with neat methanol with few operational changes. The third part comprises hydrogen enrichment to neat methanol operated engine. In this section chapter, a wise summary of the entire work has been presented.

Chapter 1 begins with a current energy requirement and its growing crisis for supply and production. It is continued with a brief introduction to methanol, a feasible alternative for renewable energy sources, and its sustainability for the near future. Also, it includes a glimpse of historical background, different production techniques, areas of utilization, impacts over the global economy, and the present scenario in the field of the transport sector. The primary focus is on using methanol as an IC engine fuel and its characteristics advantage over the other conventional fuels.

Chapter 2 includes a summary of the literature study conducted for the present research work. This part comprises a broad set of study materials related to methanol and its uses in the past years. Besides, it also highlights the technological advancement that occurred during this period. Methanol fueled IC engines usually operate with few operational changes and with modified engine components. Hence, a brief explanation of the effect of operating parameters on engine characteristics along with the cited references is presented here, for example, the compression ratio, spark timing, and fuel injection techniques. The survey comprises of different methods employed to utilize methanol as combustible fuel in IC engines. A brief introduction to gaseous fuel hydrogen is also included, along with its physical and chemical properties compared to methanol and gasoline.

Chapter 3 gives an insight into the motivation behind the present research work. It primarily focuses on objectives framed based on recent trends and research gap in the area of utilizing methanol as a primary fuel in SI engines. The research plan and the systematic experimental arrangements conducted to complete the proposed work are presented in this section. This part of the thesis also covers the details of the experimental setup arranged and the measurement techniques implemented. A detailed explanation of the devices presented here. The engine operational changes and the suitable arrangements incorporated are explained in this section.

Chapter 4 presents the hypothesis of the detailed work conducted. It includes results obtained from the different experimental trials, and a suitable explanations are highlighted. The detailed study of change of operating parameters and its effect on engine performance and emission are presented. The possible reason for the obtained results are discussed, and useful suggestions are provided with valid references. The study conducted to investigate the potential of methanol used as an IC engine fuel with different trials is discussed methodically, and a comprehensive analysis of results has been undertaken.

Chapter 5 concludes the motive of the research work. It gives an agreeable clarification of the presented work and its positive outcome. Finally, it suggests the scope of future work and the possibility of interdisciplinary research collaboration.

CHAPTER 2

LITERATURE SURVEY

The review reports collected from many sources, such as international journal publications, conference proceedings, and book chapters related to the selected topic and research area, are presented in this chapter. The detailed research findings, and valuable suggestions from the research articles were studied before the commencement of the present work. The assessment is mainly focused on identifying the utilization of methanol as a combustible fuel for IC engines, thus providing a hope to avoid the dependency on petroleum feedstocks. Reducing harmful gaseous release and restricting it within the norms is the primary area of focus in this investigation. Further, the last section includes the study of hydrogen gas and, more importantly, the effect of hydrogen enrichment on IC engines.

2.1 History of Methanol as a Transport fuel

Concerning to our research interest, it is noted that, alcohols have been considered favorable option as transport fuels since the start of IC engine development (Masum et al. 2014, 2015a). In the early 19th century, European agriculture machinery powered by a steam engines was fueled by ethanol-fueled IC engines. It followed up being the fuel of great interest for the noted scientist's Otto and Ford (Küüt et al. 1977).

Since the 1970s, evaluation of methanol usage and methanol-gasoline blends in different vehicles has been tested. The investigation emphasized fuel blending, engine modification, and testing. Agencies such as EPA and ERDA, with partial financial support from the US government, are started evaluating methanol as an alternative fuel during the early ’70s. Automotive companies such as Ford Motors, Chrysler Corporation, and General Motors Corporation have also expressed interest in this period (Pefley, R K, Browning, L H, Hornberger, M L, Likos, W E, McCormack, M C, and Pullman 1977). University of Santa Clara, Stanford University, Bartlesville Energy Research Center, and many research laboratories started developing vehicles fueled with methanol blend or the neat methanol (Patterson et al. 1980). The German Alcohol

Fuel Test Program was conducted from 1979 to 1982. Federal Minister for Research and Technology (Menrad and Nierhauve 1983) funded German automotive companies, universities, and research centers to concentrate on using 15% methanol blend in gasoline engines and check for its productivity.

With the persistent efforts, China has reached the stage where it is one of the world's leading countries to commercialize methanol-fueled vehicles and gained momentum in producing and developing methanol vehicles on a large-scale. In 1995, the first methanol pilot project was initiated in China with the Sino-American scientific association. Ford Motors assisted this collaboration by developing the first methanol engine in China (Kostka and Hobbs 2013). The nation wise emphasis on promoting methanol fuel for automobiles was started in 1998 and continued till 2008. However, the interest shifted towards electric vehicles after that, and the subsidies and privileges slowly declined for the methanol vehicles(Yang and Jackson 2012). Even though the government approval of national standards for the M85 gasoline-fueled engines in 2009 was sanctioned, china's government still reluctant to give commercial acceptance to methanol blending. India, on the other hand, has launched the program in the name of 'Methanol Economy,' initiated by NITI Ayog. It aims to reduce the nation's crude oil import bills and promote renewable energy sources. The principal objective of NITI Ayog is to introduce methanol in the transport sector with little modification to the existing engine. It can bring huge FDI investment by collaborating with global engine manufacturers and create job opportunities.

2.2 Characteristic study of Methanol blends

Imposing strict emission norms and ever increasing demand for petroleum fuels have attracted using additives with conventional fuels. The concept of blending methanol as an additive to gasoline to improve engine performance, combustion efficiency, and reduce emission are reported in this section. Due to methanol's favorable properties as a combustible fuel for the gasoline engine, many experimental trials were carried out to study the effect of different blend ratios of methanol and gasoline (Agarwal et al. 2014a; Bilgin and Sezer 2008; Nuthan Prasad and Kumar 2019). The outcome of previous investigations has suggested that the addition of methanol between 5-15 percent in volume to gasoline has shown an enhanced engine performance and higher efficiency than the conventional fuel.

The enhancement of octane rating and oxygen content in the IC engine fuels have shown significant improvement with engine characteristics(Eyidogan et al. 2010). Octane rating is essential to fuel property in the SI engines; it allows increasing compression ratio to maximum (Wang et al. 2019). Methanol blending increases the operating fuel's octane rating, and hence blends always perform better than conventional fuel with increasing compression ratio(Bilgin and Sezer 2008; Gong, Liu, et al. 2016). In his paper, Nikola Rankovic et al. tried to suggest comprehensive data about the design of the fuel matrix with required octane properties, where his research provides the knowledge of the octane requirement of an SI engine (Rankovic et al. 2015).

The current practice uses the high octane oxygenated organic compounds as a replacement for lead-based additives(Al-Farayedhi et al. 2004). The most common oxygenates used as additives for SI engine fuel are MTBE, methanol, and ethanol. Methanol being the high octane oxygenate chemical compound, shown significant improvement with performance and reduced the emissions to an impressively low level. It brings high resistance towards knock, it has less carbon content, and more oxygen, the oxides of carbon and nitrogen emission is reduced, the combustion characteristics have significant improvement provided a suitable modification to the engine (Al-Farayedhi et al. 2004; Awad et al. 2018; Liu et al. 2014).

Apart from studying the physicochemical properties of methanol/gasoline blends, the study of optimization of different blend ratios and their effect on engine performance and emission provides excellent information for the future of alternative fuel research. Abu-Zaid et al. (Abu-Zaid et al. 2004) concluded that the M15 fuel blend exhibits higher power and good performance than other blend proportions. The methanol blend ratios considered for this study are between 3%-15% in volume for gasoline. All the reviews on the varying methanol blend proportions with gasoline have suggested a similar trend with power output and conversion efficiency compared with gasoline-fueled engines, because methanol has only 46% of gross energy content as that of gasoline. Ford dedicated a fleet to the development of M85 flexible fuel vehicles, these first generation FFV's have displayed considerable improvement in power and efficiency compared to gasoline powered vehicles (Nichols 2003). (Siwale et al. 2014) studied the effect of single alcohol/gasoline and double alcohol/gasoline blend on engine characteristics, they found that both the blend types (M70 and M53b17) shown better results compared to gasoline. The knocking originates when there is an interaction between the in-cylinder pressure wave and HRR due to auto-ignition. Simultaneously, with just 5% methanol addition, the intensity of chemical reaction can be lowered, and it also reduces the tendency to knock (Feng et al. 2019).

Many researchers conducted studies to use methanol blends with gasoline have shown similar results in brake thermal efficiency, brake specific fuel consumption, power, and engine emission. In the observations conducted, with the increase of blend percentage the BTE, volumetric efficiency increases, whereas specific fuel consumption also increases with decrease is power due to lower heat content of methanol (Abdu and Inambao 2018; Agarwal et al. 2014b; Bilgin and Sezer 2008). However, the SI engine fueled with M85 despite losing power showed a considerable drop in CO and NO_x emission (Yanju et al. 2008). Lately, the numerical investigation conducted using computational fluid dynamics coupled to chemical kinetics has been very handy in studying the effect of change of engine parameters on performance, combustion, and emission characteristics (Gong, Li, et al. 2016; Gong, Peng, et al. 2018; Gong, Si, et al. 2018).

2.3 Effect of using neat Methanol as fuel

Methanol a potent automotive fuel, having the inherent advantage of good physical and chemical characteristics suitable for combustion. The idea of developing a highly efficient methanol engine was thought of long back in the 1990s by Southwest research institute; they proposed the replacement of diesel engines into high compression ratio SI engines fueled with neat methanol (Brusstar et al. 2002). The study suggests increasing BTE by 40% over the wide range of speed and load than a conventional diesel engine. Zhen et al.(Zhen and Wang 2013a; b, 2015) studied the combustion, performance, and emission characteristics from high compression ratio methanol engines. The trials were conducted on the four cylinders, direct injection diesel engine modified to operate with neat methanol. Due to the lower heating value of methanol, there will be a problem during the start at cold regions, Li et al.(Li et al. 2015) presented a detailed study of the critical firing and misfiring boundary of an SI engine fueled with methanol. The paper suggests using secondary firing aid for the methanol engine operating below 16° C due to poor cold start. However, despite having good physical and chemical properties suitable for IC engine fuels, methanol lacks a higher energy content.

2.4 Effect of Operating Parameters

This section involves the study conducted on neat methanol and gasoline/methanol blends fueled in the IC engine. The experimental and numerical investigation of changing various operating conditions and operating parameters are presented in the literature study. The study materials related to the effect of Varying ignition time (Li et al. 2010; Liu et al. 2007), the influence of air-fuel ratio (Yanju et al. 2008), enrichment of gaseous fuel (Gong, Li, Chen, et al. 2019) and the effect of changing compression ratio (Gong, Liu, et al. 2016; Liu et al. 2015), are mainly focused in this section of the study.

The open literature includes new research topics on performance enhancement techniques to improve the conversion efficiency of the methanol fuel. Reformed exhaust gas recirculation concept (Nguyen et al. 2019) and the ternary blend concept called GEM (Gasoline, Ethanol, and Methanol) are the interesting topics upon which research is conducted. The idea of adding water to methanol has implications on charge ignition and flame extinction(Verhelst et al. 2019).

2.4.1 Varying Compression Ratio:

The higher octane number of methanol attributes to improved antiknock characteristics in gasoline, enabling the gasoline-fueled engine to operate at higher compression ratios(Liu et al. 2015). Increased compression ratios could yield 5 to 20 percent more power (Gong, Liu, et al. 2016). When peak pressure and temperature decrease with lower CR, the heat losses inside the combustion chamber become greater, increasing BSFC (Roberts 2002). Increasing CR of the SI engine while running with methanol, increases brake thermal efficiency and torque substantially and releases significantly less CO, CO_2, and NO_x emissions (Çelik et al. 2011). The injection and ignition strategies on the SI engine fueled with methanol and the effect of injection nozzle parameter on regulated emissions were studied and concluded methanol engine can burn smokeless (Gong et al. 2011). The regulated (CO, HC, and NO_x) and unregulated emissions (formaldehyde and acetaldehyde) from M15 and M25 blends were tested, it was found that there was a decrease in CO and HC emissions. Simultaneously, NO_x was higher than gasoline, and methanol blends yield more unregulated gases (Ni et al. 2014). Gong et al. [9] investigated pure methanol combustion under three compression ratios (CR), 14:1, 15:1 and 16:1. The CR was varied by changing the piston bowl shape and found CR16:1, achieved a highest thermal efficiency without the occurrence of knock.

The scope of study with respect to hydrogen fuel is wide, where the hydrogen addition to different fuels has a different operating parameter. However, variation of compression ratio is one of the important parameters to check while conducting a performance analysis. The papers have suggested that higher operating compression ratio engine provides advantage of improved thermal efficiency, increased power output and decreased residual gas fraction [32,35]. Gong C. [47] studied the hydrogen assisted combustion for medium compression ratio DISI methanol engine; their results shows the improvement over combustion stability and scope of increasing the lean burn limit to excess air ratio.

2.4.2 Varying Ignition Timing:

Ignition timing is the important engine parameter for the study of combustion characteristics. There are very few papers focused on the effect of ignition timing on engine characteristics fueled by neat methanol or high-volume methanol blends. Some of the papers available are based on the study of engine load control strategy for the methanol-fueled engine (Xie et al. 2013), the sensitivity of oxygenated fuels on change of ignition timing (Daniel et al. 2012), performance and emission study for blends and pure methanol (Danaiah et al. 2014; Li et al. 2010). Danaiah et al. (Danaiah et al. 2014), reported the effect of changing ignition timing for a lower volumetric methanol blend ratio. He reported improved combustion characteristics with methanol blends; similarly, there was a significant improvement with performance parameters, such as

BTE, BSFC, and volumetric efficiency. The overall decrease in emissions (CO, HC, NO_x) was noted with methanol addition.

The Numerical analysis also suggested that there will be an optimal timing for the formation of ideal combustible air/fuel mixture (Gong et al. 2017).

2.5 Effect of Hydrogen enrichment

Hydrogen is one of the prospective sources of energy with high energy density per unit mass. It is available in abundance with combination of other compounds; hence, it is also called a secondary energy source. A diatomic molecule, which is chemically active by forming molecules such as water, combining with oxygen and carbon, forms a series of hydrocarbon chains with varying molecular structures. Hydrogen is perhaps the perfect fuel given its infinite source capacity and clean-burning characteristic compared to various alternatives considered today and thus emerging as a promising fuel source for the future.

The effect of hydrogen/gasoline combination has shown a critical observation on the usage of hydrogen in SI engines, where the decrease of bmep with an increase in hydrogen fraction, BTE increases with H_2 fraction, peak pressure and temperature increases, the flame propagation and development time reduces (Du et al. 2016; Ji and Wang 2009; Niu et al. 2016). The previous studies related to the use of hydrogen gas in IC engines have focused on blending hydrogen with gasoline or diesel and check for the characteristic improvement with the addition (Elsemary et al. 2016; Şöhret et al. 2019; Wang et al. 2014; Yu et al. 2019). The researchers studied and documented the effect of enrichment of hydrogen to gaseous fuels (Cattelan and Wallace 2010).

Similarly, hydrogen was also added to alternative fuels such as methanol, ethanol, and other bio-oil sources; surprisingly, researchers found a great deal of improvement with the combustion, performance, and reduced emissions (Gong, Li, Yi, et al. 2019; Zhang et al. 2014, 2016). The study conducted with alternative fuels and hydrogen is more promising for the near future.

Further, efforts were put into studying the use of pure hydrogen in the IC engines. However, results concerning combustion, performance, and emission were impressive, but the economical, storage and safety prospect of hydrogen in the automotive sector is still a matter of concern (Verhelst and Wallner 2009).

2.6 Summary of Literature Review

The literature review conducted provides an overview of current trends, identification of supportive theories, methodologies, source evaluation, and the report of insufficient information or a research gap.

The present investigation, primarily focused on highlighting methanol fuel as the potential replacement for the diesel and petrol for IC engines. The rise of methanol demand is by 2.5 times approximately in the past ten years; similarly, there is an increase in methanol production capacity by around three times. It is clear from the literature data that, within few years of time, methanol's production capacity may satisfy the worldwide demand and achieve mass production.

Further, methanol is favored for the IC engine fuel based on its physical and chemical properties. A higher octane number favors a higher compression ratio, knock resistance, and downsizing; high latent heat of vaporization aids good volumetric efficiency, good brake thermal efficiency; higher flame speed improves the combustion characteristics. The experimental and numerical investigations were conducted to study the performance, combustion, and emission characteristic of both CI and SI engines fueled with neat methanol or the combination of diesel/gasoline/gaseous fuels.

Methanol operation requires certain modifications to the setup and the change in operational parameters. The different possibilities of methanol usage are studied, and the valuable outcomes and suitable suggestions are documented. Few notable applications of methanol as an IC engine fuel are methanol/gasoline blends, methanol/diesel blends, methanol/gasoline/LPG ternary blends, tested on regular engine setups, and compared with the baseline results.

The operational changes implemented are varying compression ratio, direct injection, port injection, flex-fuel operation, and EGR techniques were also tested. Economic benefits and the effects of methanol on human health and the environment had been addressed. The low carbon content of methanol releases lower harmful exhaust gases, and oxygen helps complete combustion, hence reducing overall emissions from the engine exhaust. Since methanol having lower heat content, the investigations have shown that the hydrogen-enriched methanol engines provide better performance efficiency and improved combustion. Since hydrogen is noncarbonaceous fuel, it lowers harmful emissions than traditional mono fuel-powered engines.

2.7 Research Gap

The present investigations have been conducted considering the information collected from the different scholarly sources, starting from the history till the latest updated open article. As mentioned in the previous section, many studies focused on the effects of using methanol blend, the effect of change of operational parameters, and other applications are well documented in the open-source.

However, there has not been a significant study on the effect of varying engine operating parameters for high fraction methanol blends fueled in the standard SI engine model, especially on change of compression ratio, ignition timing, and injector open timing.

The study here provides the convenience of the use of methanol in IC engines with minor operating changes. The present study also shown the performance of SI engine fueled with henanced with hydrogen in methanol fuel at the idle and part load conditions. It is observed that, limited papers/resoursees are available on combustion characteristic of a hydrogen-blended methanol engine at high loads and lean conditions. Work-related to turbocharging augmented to the neat methanol-fueled engine and additionally hydrogen-methanol mode of operation is limited.

It also guides the researchers to explore the effect of change of operating parameters with a small modification to the existing engine can operate with neat methanol. Finally, spreading a positive intention to use methanol on a large scale and appeal for subsidizing and promote methanol as a long-term energy option for the world. Hence this will lead to defining the objectives of the research work for the fulfillment of the research gap.

2.8 Objectives of The Proposed Work

Research Objective:

- The primary objective is to investigate the performance, combustion, and emission characteristics of four-stroke, single-cylinder SI engine fuelled with **neat Methanol**

Specific Objective:

- To investigate the performance, combustion, and emission characteristics of four-stroke single-cylinder SI engine fuelled with **Methanol/Gasoline blends** of different percentage in volume.
- Optimization of operating parameters such as **ignition timing** and air/fuel ratio of **Methanol/Gasoline blends** to obtain good combustion characteristics
- To study the effect of **compression ratio** on performance, combustion, and emission characteristics of methanol fueled SI engine at different engine speeds.
- To study the effects of **ignition timing** on performance, combustion, and emission characteristics of methanol fueled SI engine at different engine speeds.
- To study the effect of enhancing the H/C ratio by adding hydrogen to methanol and making a comparative study on engine performance, emission, and combustion characteristics.

CHAPTER 3
EXPERIMENTATION

3.1 Experimental test set up and detailed methodology

The present work is to investigate feasibility of methanol fuel in single cylinder four stoke SI engine; it includes a suggestion for suitable modification, optimizing the operating parameters, and implementing performance-enhancing techniques to obtain the desired output. In this chapter, the instruments used to achieve the above goals are discussed with detailed experimental methodology. A single-cylinder four-stroke SI engine with varying compression ratio and ignition timings is used in the present investigation. A brief description of control systems and measuring instruments (fuel flow rate, airflow, water flow, speed, and load) are mentioned. Further, an open ECU (Electronic Control Unit) used to control the engine operating parameters such as injector open time (fuel flow rate) and ignition timing are highlighted here. Finally, hydrogen enrichment and supply techniques are also discussed.

3.2 Details of Engine setup

The experimental test rig consists of a 0.661-liter single-cylinder water-cooled naturally aspirated Kirloskar TV1 series compression ignition engine, generally used for gen-sets and pump sets, aptly modified to operate as an SI engine. The diesel fuel injector is replaced with an electronically-controlled CDI spark plug; the intake line is converted from only air supply to an EPFI intake system with a throttle body arrangement. The mechanical fuel pump initially installed with the engine is removed, and the cylinder block is modified as a variable compression ratio (VCR) system. A pressure transducer (PCB Piezotronics, Model SM111A22) is installed in the cylinder head to measure in-cylinder pressure. The 16-bit analog input DAQ (NI-USB-6210) is used to interface the signals to the computer for graphical analysis by Lab-View based program. The program provides performance and combustion analysis. An Eddy current dynamometer (Make-Technomech, Model- TMEC10) is coupled to the engine for loading. The schematic of an engine test setup used for experimentation is shown in Figure 3.1, and the engine specification is given in Table 3.1.

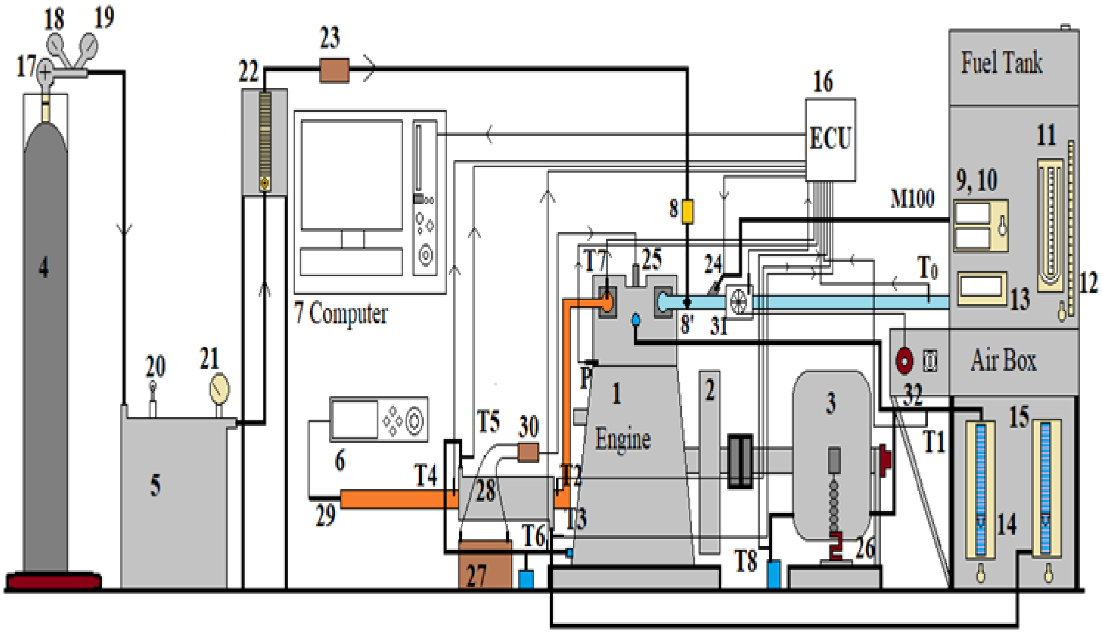


Figure 3.1 Schematic diagram of Engine lab setup

1: -	Engine	2: -	Flywheel	3: -	Dynamometer
4: -	Hydrogen Cylinder	5: -	Wet Type Flame Trap	6: -	Exhaust Gas Analyzer
7: -	Computer	8: -	Non-return Valve	8': -	Hydrogen injection nozzle
9: -	Temperature Display	10: -	Load Display	11: -	Manometer
12: -	Fuel Burette	13: -	RPM Display	14: -	Engine Rotameter
15: -	Calorimeter Rotameter	16: -	Engine Control Unit	17: -	Control Valve
18: -	Line Pressure Gauge	19: -	Delivery Pressure Gauge	20: -	Safety Valve
21: -	Pressure Gauge	22: -	H_2 Rotameter (LPM)	23: -	Dry Flame Trap
24: -	M100 Port Fuel Injector	25: -	Spark Plug	26: -	Load Cell
27: -	Battery	28: -	Calorimeter	29: -	EGA Probe
30: -	Capacitor	31: -	Throttle Body & Regulator	32: -	Throttle Control Knob
T_0: -	Ambient Air Temperature	T1: -	Cooling Water Temperature at Engine & Dynamometer Inlet	T2: -	Exhaust Gas Temperature at Calorimeter Inlet
T3: -	Cooling Water Temperature at Calorimeter Inlet	T4: -	Exhaust Gas Temperature at Calorimeter Outlet	T5: -	Cooling Water Temperature at Calorimeter Outlet

T6: -	Cooling Water Temperature at Engine Outlet	T7: -	Exhaust Gas Temperature at Exhaust Manifold	T8: -	Cooling Water Temperature at Dynamometer Outlet
P: -	Engine Cylinder Pressure Piezo Sensor	P’: -	Inlet Manifold Pressure Sensor at Throttle body		

Table 3.1 Detailed Engine Specification

Engine	Research Engine test setup one cylinder, four-stroke, Multi-fuel VCR with open ECU for petrol mode (Computerized)
Cylinder Bore	110 mm
Cylinder Stroke	87.5 mm
Compression Ratio	08-10 (Variable)
Rated Power	4.5 KW @ 1800 rpm
Ignition Timing	24° BTDC
Dynamometer	Water-cooled Eddy current type with the loading unit
Crank angle sensor	Resolution 1 Deg, Speed 5500 RPM with TDC pulse
Data Acquisition device	NI USB-6210, 16-bit, 250kS/s
Electronic Control Unit	PE3 series ECU, full build potted enclosure

3.3 Description of Experimental test rig arrangement

The experimental lab setup view presented in Figure 3.2 has a panel box consisting of an airbox of rectangular shape at the base of the panel. The airbox is fitted with a mass flow sensor and an orifice type manometer for manual reading. The fuel storage tank at the top of the set-up is also rectangular shaped with two compartments with capacity of 7.5 liters each. A burette is provided with a manual three-way valve for fuel measuring, a signal interface for air and fuel flow measurements, a process indicator, and an engine indicator.

Table 3.1 gives the specification of measurement devices used in the experimental trials. The engine exhaust gas is cooled through a water-gas heat exchanger type calorimeter. Two Rotameters installed are used for the calorimeter, and the engine dynamometer water flow measurement. One K type thermocouple 1.5mm diameter is installed in the exhaust manifold which can measure up to 1,260°C and six RTD temperature sensors, one for water supply to set-up, one each for water exit from the engine, calorimeter and dynamometer respectively, one thermocouple for exhaust gas inlet to the calorimeter while the sixth thermocouple is installed for exhaust gas out of calorimeter. A temperature sensor of the RTD type is too installed to measure ambient temperature. The whole unit enables the study of engine performance parameters.

Figure 3.2 Experimental Lab Setup

Table 3.2 Measurement devices and specification

Equipment	Specifications
K TYPE THERMOCOUPLE	Thermocouple grade wire, (−270 to 1,260°C) Standard: ± 2.2°C or ±0.75%
RTD Temperature Sensors	PT100 Series, Sensing Element: Single 100-ohm platinum (Pt 100), 3-wire; TCR = 0.00385 ohm/ohm/°C Probe: 6mm, 316 stainless steel sheath, single RTD is embedded in alumina powder Sensitivity:Class A ±[0.15 +0.002 |t|] °C, 5 seconds response time Range: 0°C to 1150°C
Airflow measurement transmitter	Accuracy ≤0.25 (BFSL) % of span Response time (10-90%) ≤1 ms
Load cell	Zero balance (FSO) ±0.1 mV/V Tolerance on output (FSO) ±0.25% Non-linearity (FSO) <±0.025%
Piezo-sensor	Rise time- 2 ms Sensitivity - 1 mV/psi Resolution-0.1 psi Resonant frequency - 400 kHz Low frequency response (-5%)- 0.001 Hz Discharge time constant - 500 s

3.3.1 Variable Compression ratio arrangement

Tilting cylinder block arrangement is moved with the help of a push screw system designed to change the engine's compression ratio. The compression ratio can be changed while the engine is still running without making any significant changes to the combustion chamber geometry. The original setup was modified from Conventional CI engine to SI engine, by changing the connecting rod length and placing thick cylinder liner. The compression ratio was reduced from 22:1 to 10:1. Further, suitable arrangements were made for the present investigation to vary the compression ratio by replacing with a thin cylinder liner to operate methanol fuel in the modified SI engine. WHile increasing the CR from CR10 to CR14. The following Figure 3.3 shows the engine head with a VCR arrangement.

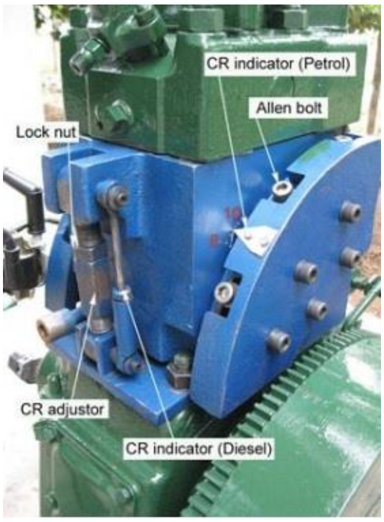


Figure 3.3 Cylinder head with VCR setup

3.3.2 Cylinder pressure and crank angle measurement

A pressure transducer (Make-PCB Piezotronics, Model S111A22), designed for dynamic measurement of compression, combustion, pulsation, blast, or explosion, is placed in the cylinder head measures in-cylinder pressure. The 16-bit analog input DAQ (NI-USB-6210) interfaces signal to the computer for graphical analysis of P-θ & PV diagrams by LabView based program. The Eddy current dynamometer is coupled with an engine for loading purposes. Crank angle encoder with trigger marked precision marker disk with 360° angle marks is mounted on the crankshaft to measure engine crank angle. The marks are scanned by a photo-electric cell, and the engine management system uses signals.

Figure 3.4 a) shows the pressure sensor used, and figure 3.4b gives the DAQ setup details.

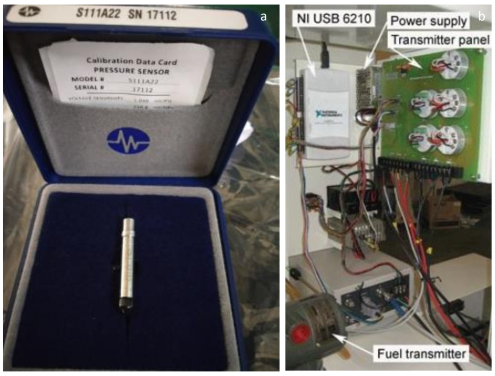


Figure 3.4 a) Pressure sensor and b) Data Acquisition System

3.3.3 Dynamometer:

An Eddy current dynamometer (Make-Technomech, Model- TMEC10), used as a loading unit, consists of an electrically conductive shaft that moves across a magnetic field to generate motion resistance. It is one of the most common and reliable absorbing type, dynamometer equipment to measure the engine's power.

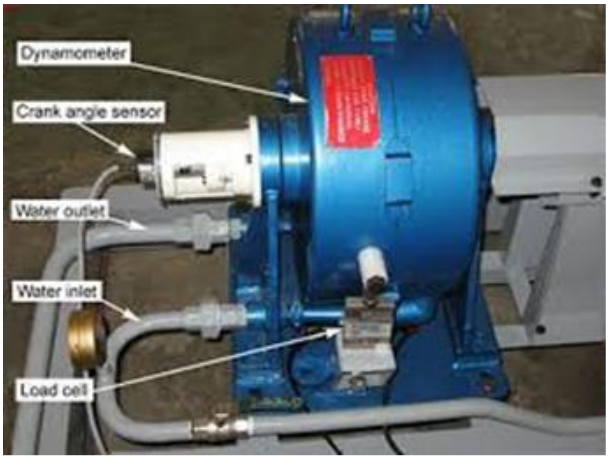


Figure 3.5 Eddy current dynamometer (AX155)

Figure 3.5 shows the dynamometer used for the present investigation. Absorber Eddy Current dynamometer is equipped with external water supply connections to the inlet flange to cool the system. A pressure gauge was installed to control a constant water supply pressure of 1.5 bar to the dynamometer.

The engine and the dynamometer connected by a rubber coupling are mounted inline on the ground. The height of the crankshaft axis coincides with the dynamometer axis on the same vertical plane. The crankshaft, which works as a rotor, is a conductive core that moves across the magnetic field generated by the stator placed in the dynamometer housing. The brake torque is transmitted from the dynamometer housing to the transducer (load cell). The dynamometer loading is controlled by a change in the electric signal proportional to the force applied to the load cell.

3.3.4 Crank Position Sensor

In the present case, a crank angle position sensor (CPS) is attached to the dynamometer hub is placed above the cylindrical gear tooth that was mounted on the output shaft.

The photograph of CPS placement is shown in Figure 3.6.

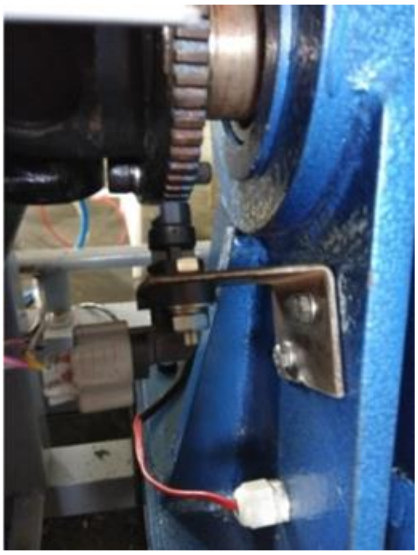


Figure 3.6 Crank angle position sensor

CPS is placed to identify the crankshaft's exact position; based on the signal received computer can control the fuel injector open time and control the spark timing. The variable reluctance type CPS is used, where a pulsed voltage signal corresponding to each tooth is produced. The missing tooth of gear mounted on the shaft generates one missing pulse per rotation, which provides the crankshaft position's reference point with respect to TDC.

3.3.5 Throttle Position Sensor

TPS is viewed as a potentiometer, basically an output signal that decides the amount of fuel supplied to the engine for smooth operation. TPS is mounted on the throttle body; it senses the throttle valve position and transmits the signal to ECU. An output current is generated based on the position of the knob, thereby controlling the airflow in the intake manifold.

3.3.6 Fuel consumption and airflow measurement

To find out the engine performance characteristics, accurate measurements of both fuel consumption and airflow quantities are essential. Fuel was delivered to the engine during the gasoline operation from a storage tank fitted over a control panel, which also consists of the burette, digital displays (speed and load), manometer, and the throttle control knob.

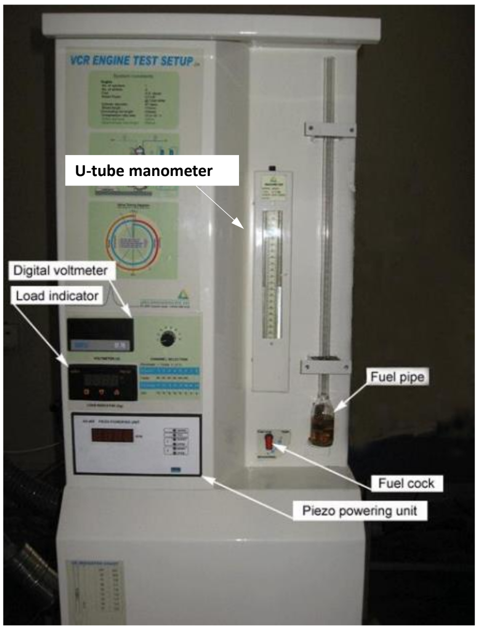


Figure 3.7 Engine panel box assembly

A volumetric gasoline fuel measurement system is adopted, where fuel consumption is noted from the glass burette mounted on the control panel. A control valve is used to switch the flow of fuel from either tank or else from the burette to the engine. Thus, the time required to consume 20cc of fuel is noted from the burette using a stopwatch. The control panel setup holds the airbox with an orifice diameter of 20 mm. A flexible tube connects the airbox with the intake manifold and a small tube connected to the U-tube manometer to measure the pressure difference in the two columns. The Fuel and airflow measurement unit fit to the panel box along with other digital displays is shown in Figure 3.7.

3.3.7 Speed Measurement

The engine used for testing is a variable speed type. An inductive pickup sensor in combination with a digital rpm indicator detects the speed and displays it for user, and it plays a vital part in controlling the eddy current dynamometer. The rotating dynamometer shaft, next to an inductive pickup, the rotating encoder sends voltage pulses, and the frequency obtained is converted into rpm. A digital indicator calibrated to indicate speed in terms of revolutions per minute is fitted to the control panel, which displays the sensed speed. A Kubler Germany makes a crank angle sensor with resolution 1 deg and 5500 speed with TDC pulse for the present case. The open ECU detects engine speed using a signal received from the crank angle sensor.

3.3.8 Exhaust gas Measurement

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
Hydro carbon	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

An AVL DIGAS 444 exhaust gas analyzer is used to measure the exhaust gas emissions of CO (% volume), CO_2 (% volume), HC (ppm), O_2 (% volume), NO_x (ppm) and the relative air-fuel ratio (λ). Table 3.3 gives the specification of the gas analyzer. Before starting the experiments like leak test, zero adjustments, and cleanliness of filters, the precautions are taken care of.

3.3.9 Installation of additional gas setup for Hydrogen enrichment

The hydrogen gas supply line consists of a two-stage gas regulator, pressure gauge, delivery valve, gas flow meter, and the wet type flame arrester arrangement. The schematic of a hydrogen gas setup is as shown in Figure 3.8.

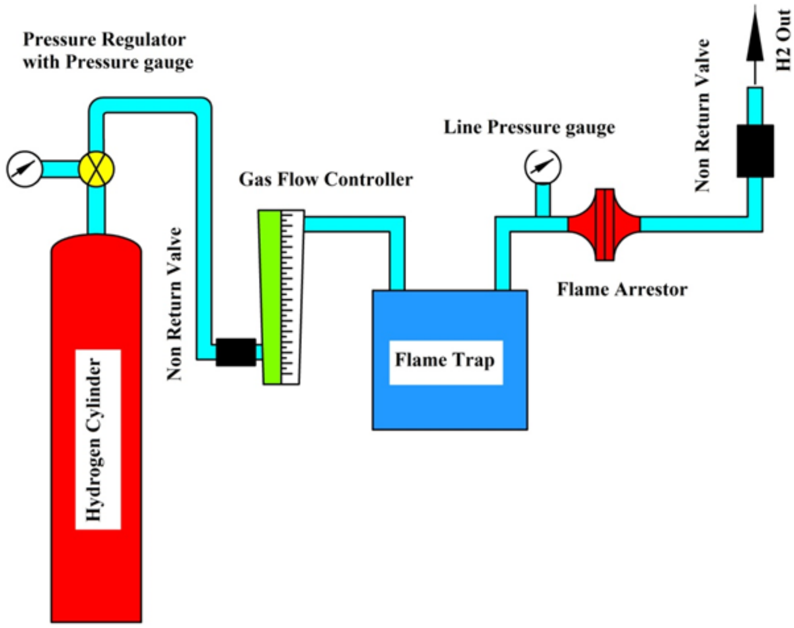


Figure 3.8 Schematic of Hydrogen gas setup

A direct read rotameter (Omega, FLDA3220ST) is used to measure the hydrogen flow rate, followed by a dry type flame arrester. The hydrogen gas cylinders procured in the gas cylinders, stored at 150 bar from the commercial vendor. Safety measures were taken to handle hydrogen gas during the experiment. A two-stage gas regulator was fitted to the cylinder to control gas flow, and a flame trap is placed before the injection system to prevent the possible backfire.

Hydrogen gas is supplied through a flame trap from the compressed gas cylinder. Between the flame trap and the gas injector, a mass flow meter is fitted. Two non-return relief valves are fitted in the fuel line, one before the flow meter and other at the end of gas fuel line before the inlet manifold. Before the injector in the hydrogen supply line, a pressure sensor was mounted to control the injector's supply pressure.

3.4 Methodology for the Present Investigation

Plan and Procedure

An overview of the experimental methodology planned during the investigation is shown using a flow chart. Figure 3.9 presents the detailed step by step procedure followed in the completion of the present study.

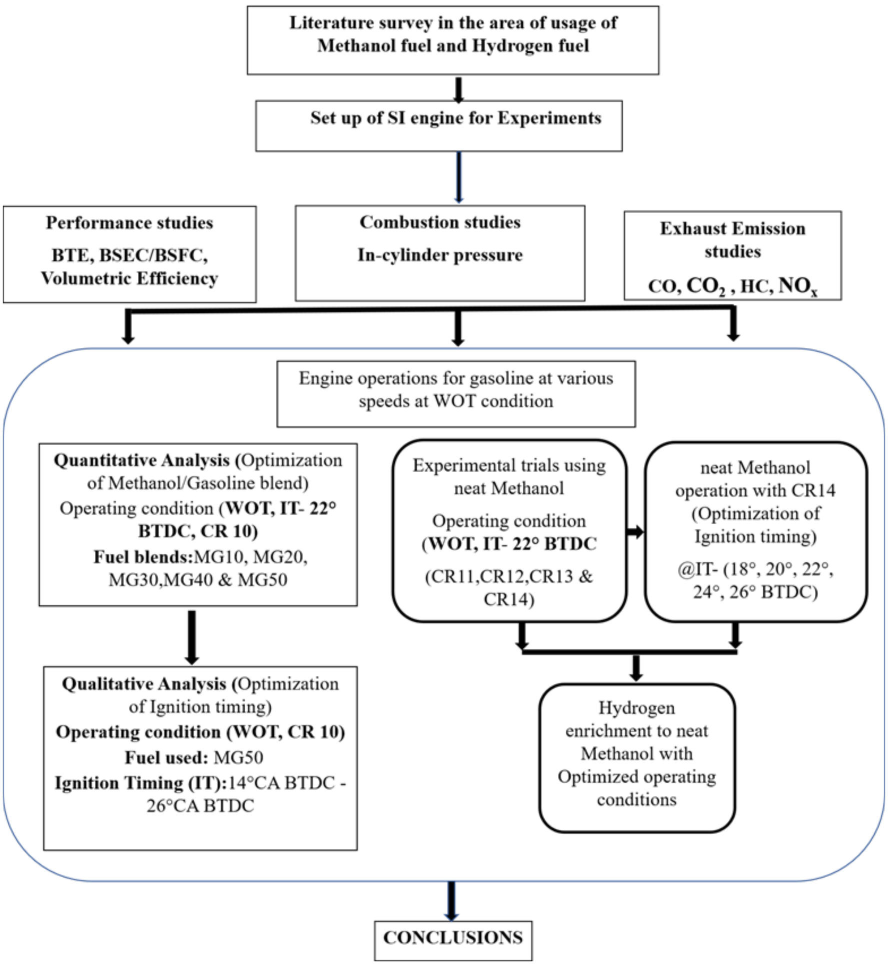


Figure 3.9 A detailed Flow chart of an experimental study

The study was done in four parts, as highlighted below.

- The first part includes an experimental investigation conducted using gasoline fuel at CR10, 22° BTDC ignition timing with varying speed and WOT operating conditions.
- The second part includes the characteristic study of SI engine fueled with Methanol/Gasoline blends of different volumetric blend percentage (10%-50%)
    1. The effect of varying ignition time (26°-14° BTDC) on engine performance, combustion, and emission characteristics are studied at different engine speed with the same operating condition.
- The third part includes the characteristic study of SI engine fueled with neat methanol conducted with suitable engine parameters
    1. Effect of change of CR (11,12,13 & 14)
    2. The effect of varying ignition time (26°-18° BTDC)
- The fourth part includes the investigation of hydrogen addition to enhance the H/C ratio of methanol fueled SI engine.

3.4.1 Description of Operating Conditions

Tested methanol fuel was industrial-grade methanol with a purity of 99.9%. The methanol is blended separately (splash blending followed by magnetic stirrer) and added to the fuel tank. The experiments was carried out for wide-open throttle (WOT) operating condition with engine load control strategy, based on varying ignition time at constant compression ratio. Experiments were performed under ambient temperature between 25°C to 32°C in dry conditions. During the experiment at each fixed CR engine was kept running for ten to fifteen minutes in the idle state and then the operating conditions are achieved gradually by increasing the throttle opening and increasing the load by keeping the speed constant at 1800 rpm. After achieving WOT for 1800 rpm, the engine was kept running till study state achived. The experimental results were noted for 1800 WOT at maximum possible load at this speed, and then further loading was done at constant throttle opening to reduce till 1200 rpm at intervals of 200 rpm. The water flow was controled to engine cooling, Dynamometer, and the calorimeter were kept at 200kg per hour.

Windows-based software package ‘Engine Soft’ supported by LAB view, gives performance evaluation graphs. The result parameters obtained are brake power, indicated power, frictional power, bmep, imep, brake thermal efficiency, indicated thermal efficiency, mechanical efficiency, volumetric efficiency, specific fuel consumption and the air-fuel ratio. The Engine soft GUI layout is shown in Figure 3.10

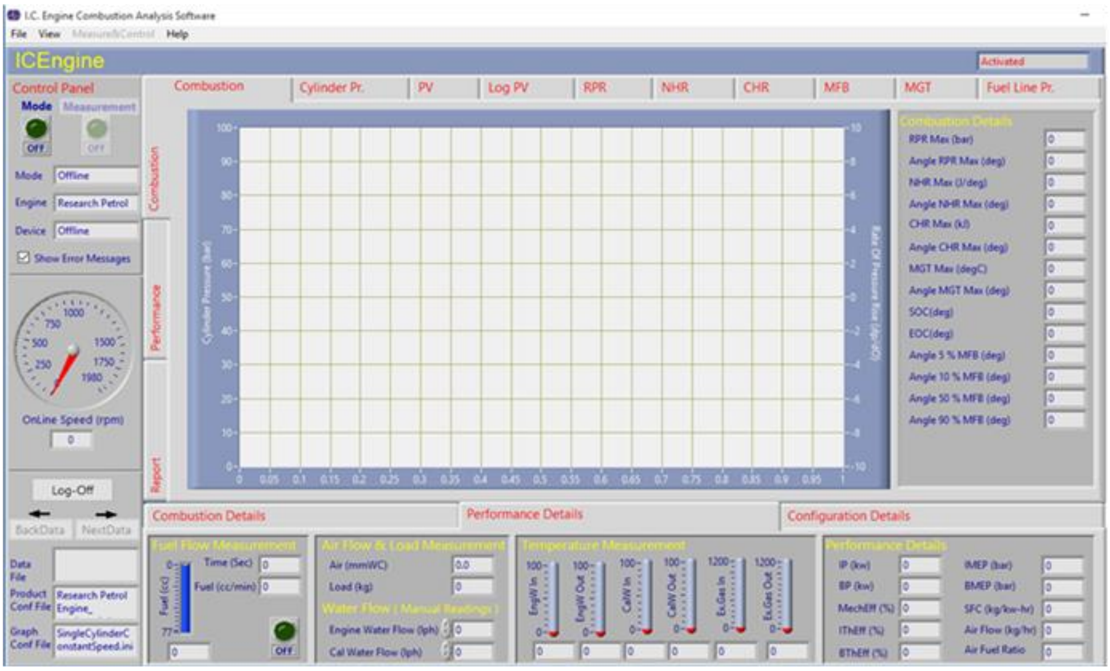


Figure 3.10 Engine soft GUI layout

The engine control system's operating parameters are controlled by open ECU. The programmable fuel injection and ignition control system is developed by Performance Electronics Ltd. The PE3 series system is an engine control unit connected to a computer through an Ethernet port. Figure 3.11 shows the image of open ECU connections used for the present investigation. PE monitor software installed on a computer controls the fuel injector open time for every engine cycle to measure fuel consumption. It also configures Ignition timing, the type of ignition, coil charge time. Figure 3.13 and Figure 3.13 presents the computer layout of the PE3_SP_monitor Ignition time tuning table and Fuel injection tuning table.

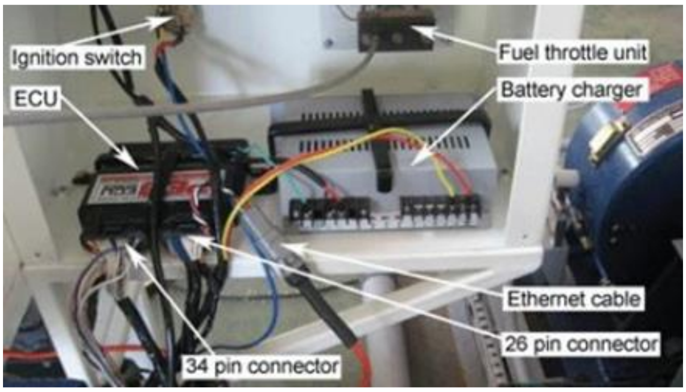


Figure 3.11 PE3 series ECU connections

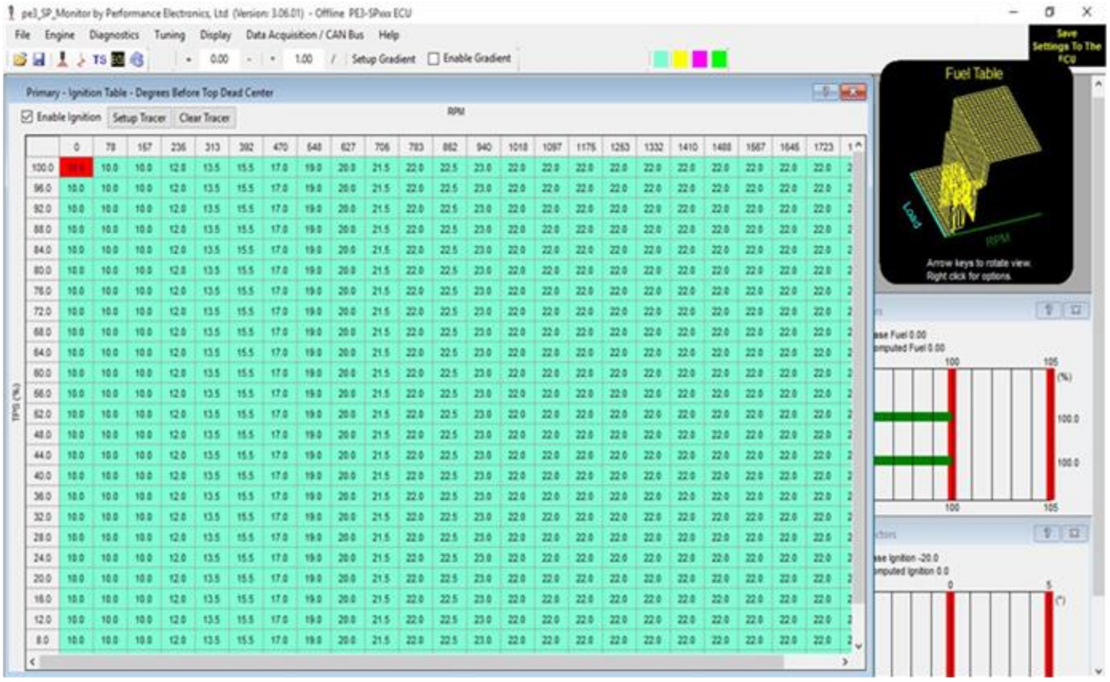


Figure 3.12 PE3_SP_monitor Ignition time tuning table

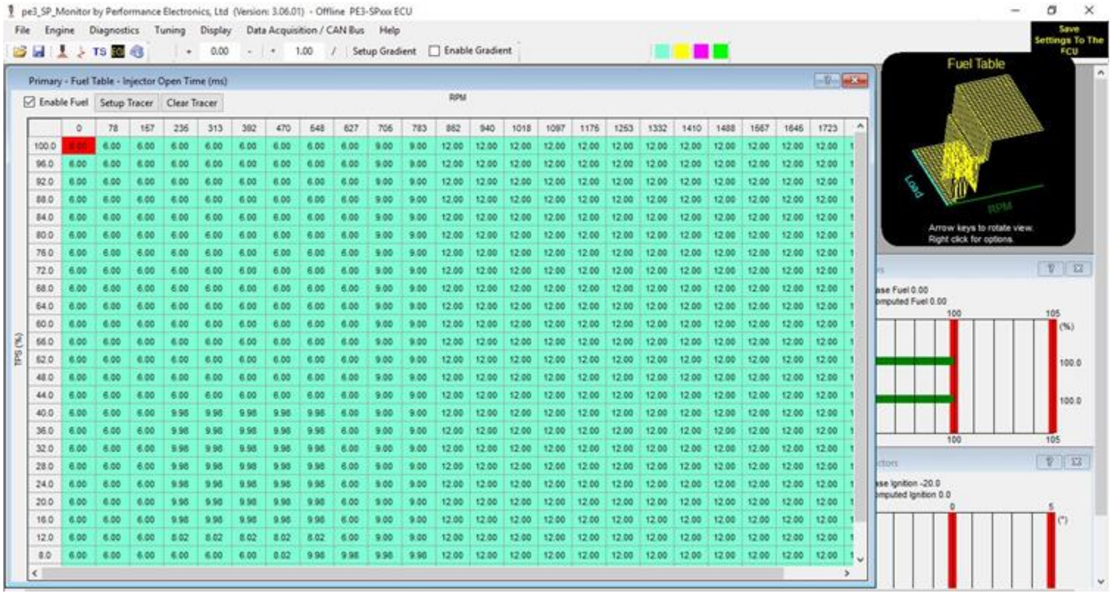


Figure 3.13 Fuel injection tuning table monitor layout

3.4.2 Plan of execution for Hydrogen enrichment

The final part of the investigation is to study the methanol fueled engine characteristics with hydrogen enrichment. The two reference characteristic data of the SI engine operating with baseline fuel gasoline and neat methanol are collected. These experimental results are collected at various speeds and WOT operating conditions. The operating parameters are optimized for the functional fuel, and hence the best possible result is obtained. The comparison of engine characteristics is conducted between preliminary investigation results and the enriched hydrogen operation results.

3.4.3 Hydrogen Enrichment

The optimized set of reading for neat methanol is selected, and the effect of enrichment of hydrogen in a small percentage is studied. The procedure followed in this study is as follows, SI engine fueled with neat methanol is operated with CR14, ignition timing of 20° BTDC, and the WOT position is maintained throughout the investigation. Hydrogen is added to the inlet manifold in the calibrated amount for different engine speeds. The readings are taken for the different hydrogen flow rates, varying between

5 lpm to 20 lpm, and the gas enrichment calculations are based on energy fraction concerning base fuel. The evaluation of performance, combustion, and emission characteristics is done for each percentage of hydrogen supply compared with the expected results of previously obtained neat methanol data. The volume flow rate calculated for hydrogen supply is calculated using the below-mentioned formula. The measured volume of hydrogen is supplied to the inlet manifold for different speeds, the change is engine characteristics in terms of BTE, BSEC, volumetric efficiency, cylinder pressure, and exhaust gases is noted and compared with the baseline readings (neat methanol readings).

The volume flow rate of hydrogen supply is calculated as per the equation,

$$\dot{v}_{H_2} = \left(\frac{\rho_{H_2} \times HCV_{M_{50}} \times \dot{m}_{M_{50}} \times x_{e_{H_2}}}{HCV_{H_2} \times \left(1 - x_{e_{H_2}}\right)} \right) \times 60000$$

Where,

$\dot{v}_{H_2}$ is the volume flow rate of hydrogen in l/min

$HCV_{M_{50}}$ is the higher calorific value of M_{50} fuel in MJ/kg

HCV_{H_2} is a higher calorific value of hydrogen in MJ/kg

$\dot{m}_{M_{50}}$ is the mass flow rate of M_{50} fuel in kg/hr

ρ_{H_2} is the density of hydrogen in kg/m^3

x_{H_2} is the energy fraction of hydrogen

The hydrogen energy fraction x_{H_2} is calculated from equation 1 and to measure the volume flow rate of hydrogen $\dot{v}_{H_2}$, required during the experiments, equation 2 is used.

$$x_{H_2} = \frac{\in_{H_2} \times \dot{v}_{H_2}}{\in_{H_2} \times \dot{v}_{H_2} + \in_M \times \dot{v}_M} \quad (1)$$

$$\dot{v}_{H_2} = \left(\frac{x_{H_2}}{1 - x_{H_2}} \right) \times \left(\frac{\in_M \times \dot{v}_M}{\in_{H_2}} \right) \quad (2)$$

Where, energy density $\in = \rho \times hcv$

3.5 Uncertainty Analysis

The necessity of evaluation of experimental uncertainties and error is to ensure that the study conducted is validated properly. The sources of uncertainties are many, such as weather condition, calibration, observation, instrument selection, and incorrect reading. The uncertainty percentages of various measuring instruments are used to analyze dependent variables such as BTE, brake power by partial differentiation method. The overall uncertainty of the present work is found to be ±1.4%.

Kline and McClintock(1953), presented the method of calculating experimental uncertainties (Moffat 1988). This method carefully categorizes the specification of the measurement uncertainties in the conducted experiment. The uncertainty of obtained data is evaluated based on the Gaussian distribution method with confidence interval between ±2σ.

Experiments are conducted to obtain mean values of parameters ($\bar{\bar{x}}$) and standard deviation (σ_i) of any measured parameter (x_i) for a given number of readings. The uncertainties for independent parameters were found by calculating the mean, standard deviation, and standard error for the repeated set of 20 readings.

$$W_i = \frac{2\sigma}{X} \times 100$$

The overall uncertainty is investigated as below:

= Square root of {(CO)^2 + (NO_x)^2 + (load)^2 + (speed)^2 + (time)^2 + (brake power)^2 + (fuel consumption)^2 + (brake thermal efficiency)^2 + (cylinder pressure)^2 + (crank angle)^2 + (manometer)^2}

CHAPTER 4
RESULTS AND DISCUSSION

The present investigation includes the performance, combustion, and emission characteristic study of SI engine fueled with neat methanol. The main objective was to obtain the best possible results regarding power output, efficiency, and minimal exhaust emissions, compared to conventional gasoline fuel. A single-cylinder four stroke, Kirloskar TV1 series compression ignition engine, aptly modified to operate as an SI engine, was used for the experimentation. Preliminary investigations on methanol/gasoline blends and the effect of changing operating parameters are also studied to support the main objective. Finally, an experimental study was extended to check for an effect of hydrogen enrichment on the methanol-fueled engine.

The experimental results are divided into four segments. The first segment includes studying performance and emission characteristics of SI engine fueled with methanol/gasoline blends of varying volumetric mixture ratios (10, 20, 30, 40, and 50) at a compression ratio of 10:1 with a constant engine speed of 1600 rpm. In the second segment, experimental trials were conducted to study the effect of varying ignition timing on SI engine fueled with M50 fuel blend. The scope of this work is to investigate the effective blend ratio of methanol/gasoline with optimal ignition timing on performance and emission characteristics of the single-cylinder four-stroke SI Engine.

The third segment focuses on studying the effect of varying engine operating parameters (Compression ratio and Ignition timing) on performance, combustion, and emission characteristics of the single-cylinder four-stroke SI engine fueled with neat methanol.

The fourth segment summarizes hydrogen enrichment to the SI engine fueled with neat methanol and its effects on performance, combustion, and emission characteristics.

4.1 Characteristic Study of Methanol/Gasoline Blends

The quantitative analysis of different methanol/gasoline blends ratios was conducted to study the engine characteristics by keeping the operating parameters, ignition timing at 24° BTDC, and a constant compression ratio of CR10. The performance evaluation suggests the methanol/ gasoline blend within the flammability limit has shown good results compared to gasoline. However, an increase of methanol volume beyond 50% has decreased thermal efficiency and power. Because with an increase in methanol percentage, the energy content reduces and, more importantly, the fuel-air mixture becomes a very lean mixture. Hence, poor combustion results in lower power and thermal efficiency.

4.1.1 Performance Evaluation

Brake Thermal Efficiency

The engine brake thermal efficiency of different methanol/gasoline blend ratios are shown in Figure 4.1. The results suggest that brake thermal efficiency has increased with an increase of methanol addition; a maximum BTE of 27.94% was obtained for M50 fuel. However, a further increase of methanol in gasoline reduces BTE compared to M50, mainly because lean burning beyond the flammability accounts for the poor burning characteristics of the methanol fuel blend.

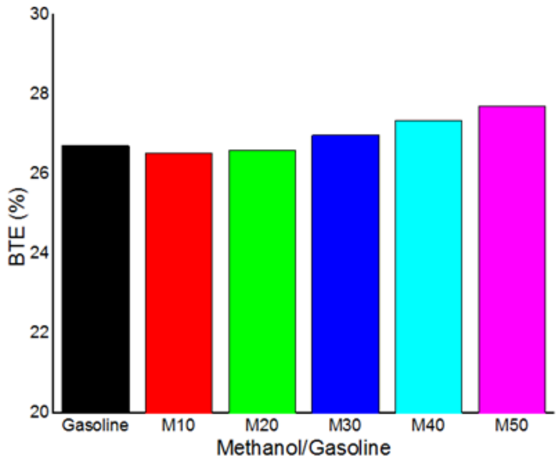


Figure 4.1 Variation of BTE for different Methanol/ Gasoline blends

The high burning velocity of methanol helps accelerate the combustion of methanol/gasoline blend in the combustion chamber (Li et al. 2017). Further, the blending of methanol in high volume means increasing more oxygen in the fuel, which allows all the available fraction of fuel to combine with oxygen and generate high combustion efficiency (Li et al. 2019). Hence M50 fuel exhibits higher thermal efficiency of 10 % more than gasoline fuel.

Brake Power:

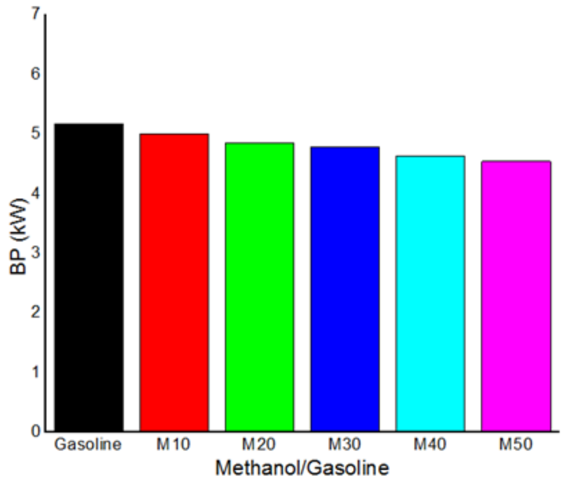


Figure 4.2 Variation of BP for different Methanol/ Gasoline blends

Figure 4.2 shows the variation of the brake power of different methanol/gasoline blends. It is observed that the highest power output of 4.8 kW was for M10 fuel among the methanol/gasoline blends. The power output reduces by 15% to 20% with the increase of methanol percentage compared to gasoline. These significant changes in engine power output were due to a reduction in the air/fuel ratio by 29 % (A/F 50% of methanol = 10.52& A/F Gasoline = 14.95). The effect of the methanol's lower energy content was also the reason for the loss of power in methanol/gasoline blends (LHV 50% of methanol is 33,084 kJ/kg & LHV of Gasoline is 46,370 kJ/kg) (Abdu and Inambao 2018). At WOT condition, engine operating at high speed and maximum load, the maximum power generated entirely depends on the fuel's energy content.

Brake Specific Energy Consumption:

Brake Specific energy consumption is a measure of energy consumption for producing the unit engine power. The comparison of BSEC for different methanol/gasoline blends is shown in Figure 4.3. The specific energy consumption for M10 fuel is 13974 kJ/kW-hr, decreasing the increase of methanol percentage, where M50 exhibits the lowest BSEC value of 12568 kJ/kW-hr. The results obtained suggest that M50 fuel is economical in terms of combustion of fuel due to higher oxygen content, higher flame speed, and large flammability limits of methanol attributed to good combustion characteristics and the properties of gasoline(Çelik et al. 2011; Eyidogan et al. 2010).

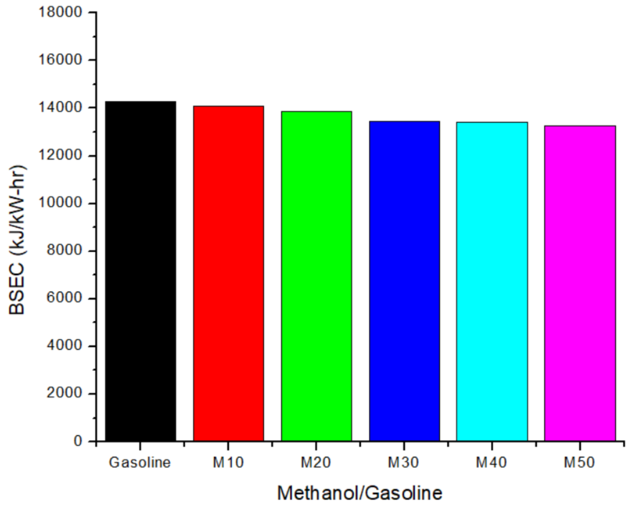


Figure 4.3 Variation of BSEC for different Methanol/ Gasoline blends

Volumetric Efficiency

Volumetric efficiency is the measure of the engine’s intake air capacity; and its influence on the engine's power output. Figure 4.4 is presented with the variation of volumetric efficiency of different methanol blends.

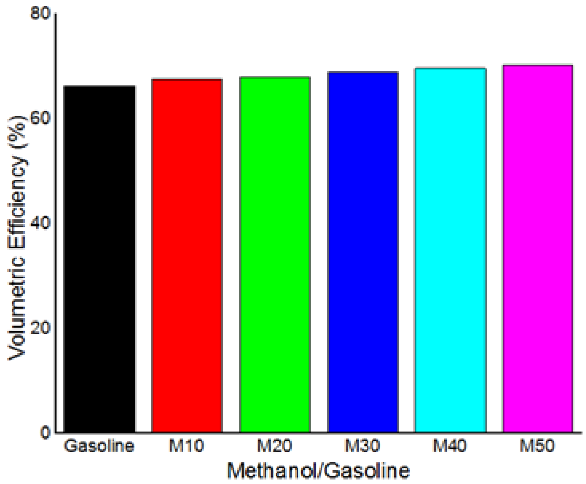


Figure 4.4 Variation of Volumetric efficiency for different Methanol/Gasoline blends

The highest volumetric efficiency value was observed for the M50 fuel blend with 70.1%. However, M40 and M30 also showed values more than gasoline of 69.6% and 68.8% compared to gasoline value of 66.2% at 1600 rpm; M10 and M20 have similar values as that of gasoline. It is observed that volumetric efficiency increases with the rise of volume percentage of methanol due to the high latent heat of vaporization, methanol cools the incoming air and increases the volumetric efficiency with the power output (Bilgin and Sezer 2008). It is apparent that higher methanol content requires higher energy to evaporate the fuel, which decreases the temperature of the air-intake pipe, and the density of air becomes greater. As a result, the engine allows more air into the cylinder, which increases the volumetric efficiency (Phuangwongtrakul et al. 2016).

Exhaust Gas Temperature

The engine's exhaust emission and cylinder temperature can be assessed based on the exhaust gas temperature (EGT). NO_x formation is commonly related to temperature change (Yücesu et al. 2006). Based on our previous performance outcomes such as BTE, BSEC, and volumetric efficiency, the combustion efficiency is best seen with M50 fuel even though it recorded a lower value of exhaust temperature of 605 °C.

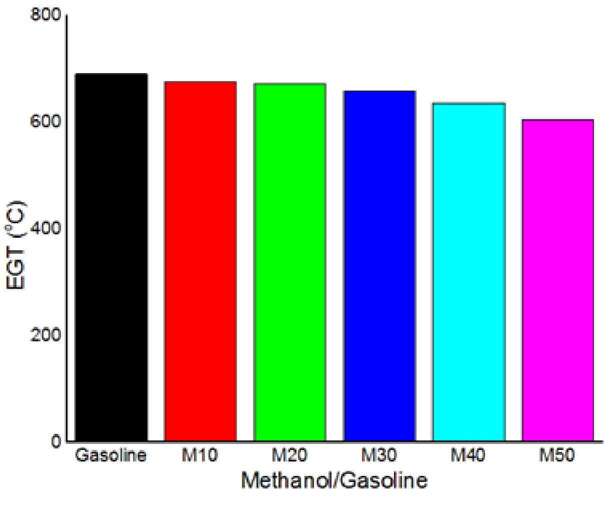


Figure 4.5 EGT variations for different Methanol/ Gasoline blends

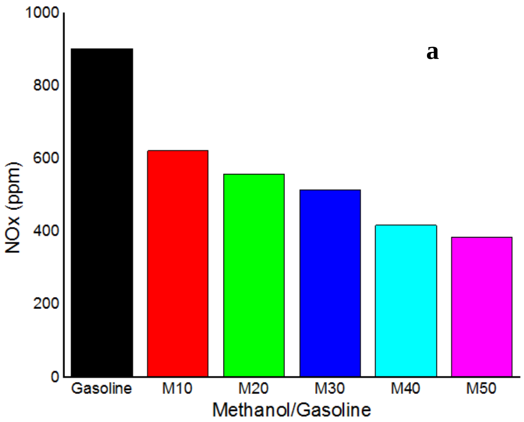
The exhaust temperature reduction is observed for M50 fuel is due to the quenching effect of the methanol present in the blend. The highest exhaust gas temperature recorded was for M10 fuel blend (684 °C) due to less quenching effect and higher heat content value of gasoline fuel. Figure 4.5 shown the variation of EGT for different methanol/gasoline blends(Balki et al. 2014)

4.1.2 Emission Characteristics of Methanol/Gasoline Blends

The exhaust emission results (NO_x, HC, CO_2, and CO) obtained from the experimental trials conducted using methanol/gasoline blends are highlighted in this section. The emission results are compared with gasoline fuel and found a good agreement of improvisation with methanol/gasoline blends.

Emission results of oxides of Nitrogen and Carbon dioxide

Figure 4.6 a) shows the variation of NO_x emission for different methanol/gasoline volume fractions operated at a constant speed and WOT conditions. The result clearly shows a decrease in NO_x value when compared to gasoline due to a mixture of low carbon-hydrogen fuel methanol, having higher latent heat of vaporization, which reduces the flame temperature and, in turn, results in lower NO_x. Simultaneously, the NO_x emission comparison between the different blend ratios observes a decrease in NO_x values with the increase of volume fraction of methanol in gasoline. M50 fuel shows the least value of 398 ppm, where M10 with lesser methanol percentage gives a more NO_x value of 603ppm, compared to other blends.



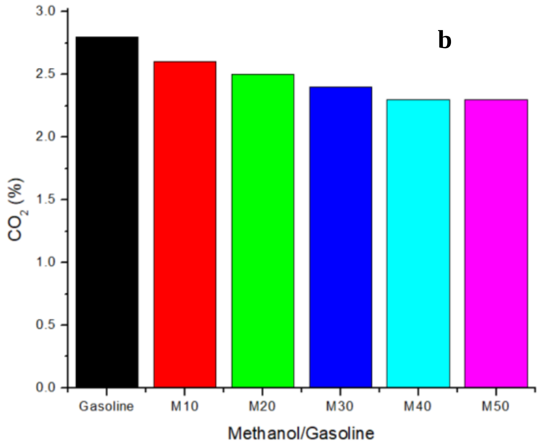


Figure 4.6 a) NO_x and b) CO_2 emission variation of Methanol/Gasoline blends

The EGT reduction in methanol/gasoline blends is by 3- 4% for M10 compared to gasoline fuel, and the further maximum reduction observed is about 15% for M50. Hence the depression of NO_x is observed in all the cases of methanol addition, because NO_x formation is often related to temperature. Usually, higher RON fuels start combustion earlier, and hence most of the heat released is utilized for the work and thus decreases the EGT (Masum et al. 2015a).

At WOT, proper mixing of air/fuel causes an increase in the fuel-air mixture's burning rate, which improves combustion. Figure 4.6 b) shows a decrease in CO_2 emissions with an increase in methanol volume fraction. It is mainly due to the lower molecular mass of methanol; the ratio of carbon and hydrogen reduces with the increase in methanol percentage in methanol/gasoline blend. More specifically, CO_2 decreases with the increase of methanol percentage among the blends. Reduced CO_2 concentration ranges from 15-20% for the different methanol/gasoline blends varying from lowest-to-highest (M10-M50).

Carbon monoxide and unburnt Hydrocarbon

CO and HC emissions are directly related to combustion efficiency; in the previous section, we studied the performance characteristics of different methanol blends. M50 fuel has shown good efficiency in terms of combustion. Hence good combustion, leads to reduced CO and HC emissions with a higher methanol fraction.

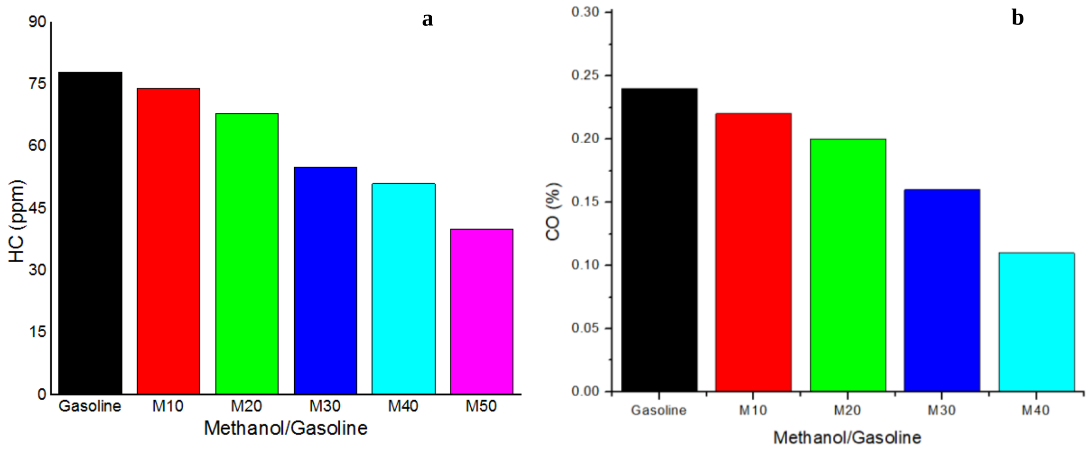


Figure 4.7 a) HC and b) CO emission variation of Methanol/Gasoline blends

Oxygenated fuel added to the gasoline provides more oxygen during the combustion process, and hence we obtain better combustion efficiency and reduced exhaust emissions (Ozsezen and Canakci 2011). The most significant decrease in both CO and

HC was observed with the M50 fuel blend operating at the constant speed of 1700rpm and WOT conditions. CO and HC emissions decrease by 47% to 55 %, respectively, compared to gasoline fuel.

Figure 4.7a) shows the unburned HC variation for different methanol/gasoline blends. It is observed from the figure that the addition of methanol helps reduce HC emission in SI engines. The reason behind this is the high flammability limit and higher flame speed of methanol. Hence, methanol/gasoline blend-air mixture, flame propagates faster and engulfs the combustion chamber quickly and thereby providing complete combustion in each cycle. Similarly, unlike HC emission CO emission also have the same effect with the methanol addition, the reduction in CO emission in Figure 4.7b) clearly attributes to the improved combustion. It also owes that methanol has extra oxygen molecule, and it contains less carbon compared to gasoline (Rifal and Sinaga 2016).

4.2 Characteristics Study of SI Engine fueled with M50 Fuel blend

The performance evaluation of methanol/gasoline blends suggested that the methanol addition has shown good characteristics with SI engine without any modification. This section of the study focuses on the effect of ignition timing on the performance combustion and emission characteristics of SI engine fueled with M50 fuel blend. The experimental trials were conducted for speed range 1400- 1800 rpm, CR10, and WOT conditions. The ignition timing was varied from 18° - 24° BTDC.

4.2.1 Performance Evaluation

Brake Thermal Efficiency

Figure 4.8 shows the variation of brake thermal efficiency of M50 blend and gasoline at different engine speeds and varying ignition timing (18°-24°BTDC). It is observed that higher brake thermal efficiency for the M50 blend operation compared to gasoline fuel. This observation was based on our previous study, which suggests the presence of more oxygen in methanol and improved burning velocity of the fuel enhances the combustion and provides better thermal efficiency (Campos-Fernandez et al. 2013). The high latent heat of the vaporization of methanol allows the mixture to absorb more heat during the compression stroke. Thus less work is required to compress the mixture, thereby improving the overall efficiency (Masum et al. 2015b).

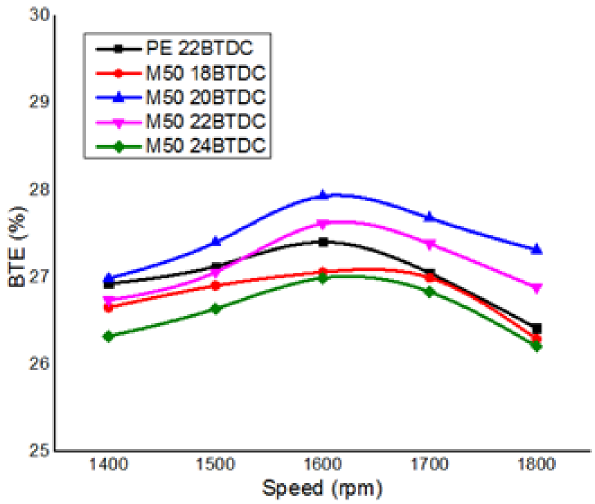


Figure 4.8 Variation of BTE of M50 fuel for different ignition timing

Figure 4.8 shows that ignition timing 22° and 20°BTDC, the improvement in brake thermal efficiency ranges from 2-5% more than that of gasoline operation. The maximum efficiency of 27.9 % was obtained at 1600 rpm and with 20°BTDC ignition timing. Retardation of ignition time has proved to be efficient because it allows methanol to absorb more temperature and atomize better to form a homogeneous mixture. The optimal ignition timing provides a shorter ignition delay, maximum cylinder pressure, higher heat release rate, and higher thermal efficiency (Li et al. 2010).

Brake Specific Energy Consumption

Figure 4.9 shows the effect of varying ignition timing on BSEC for a different engine speed of M50 blend and gasoline fuel. Agarwal et al. (2014) suggested that blending oxygenated fuels such as methanol exhibits lower BSEC compared to gasoline because alcohol blends burn efficiently. The values obtained from M50 fuel operating with 20° BTDC ignition timing show a 4% decrease in BSEC compared to gasoline. This mainly due to the presence of more oxygen, and high flame front propagation of M50 fuel allows engine to consume less energy to produce rated power.

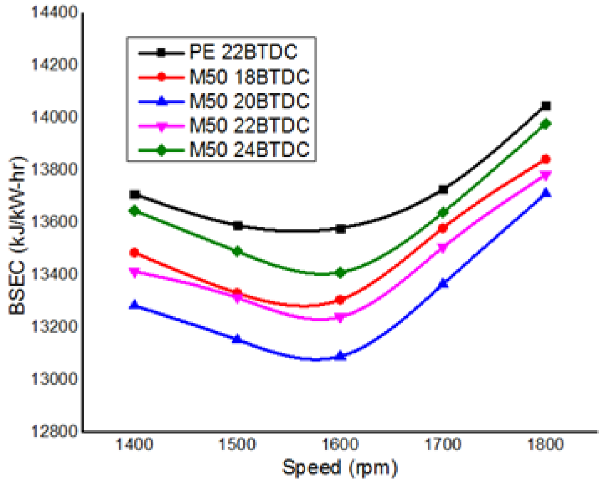


Figure 4.9 Variation of BSEC of M50 fuel for different ignition timing condition

Retarding the ignition time from 24° BTDC to 18° BTDC helps M50 fuel to improve the fuel vaporization and thus increases the in-cylinder temperature, thereby improving combustion efficiency. The lowest point in the BSEC curve is at 1600 rpm, and the value is 13590.8 kJ/kW hr. At 22° BTDC, for gasoline, whereas for M50 fuel minimum amount of energy consumption of 134007 kJ/kW hr. At 24° BTDC, 13379 kJ/kW hr at 18° BTDC, 13321 kJ/kW hr. At 22° BTDC and 13045 kJ/kW hr. at 20° BTDC was obtained at the respective ignition timing.

Volumetric Efficiency

The effect of ignition timing on the volumetric efficiency for M50 fueled SI engine operating at different speeds with WOT conditions is shown in Figure 4.10. The maximum volumetric efficiency is observed at an engine speed of 1300 rpm. The latent heat of vaporization of methanol is higher (approx. 3 times) than gasoline (Table 1); therefore, methanol absorbs more heat during the compression stroke. As soon as methanol fuel is injected in the manifold due to higher latent heat of vaporization, cools the intake air significantly, thereby increases the air density, which increases the volumetric efficiency of the engine (Agarwal et al. 2014a). It is apparent that higher methanol content requires higher energy to evaporate the fuel, which decreases the temperature of the air-intake pipe, and the density of air becomes greater; as a result, the engine allows more air into the cylinder, which increases the volumetric efficiency. This also allows more fuel injection into the chamber to satisfy air-intake demand.

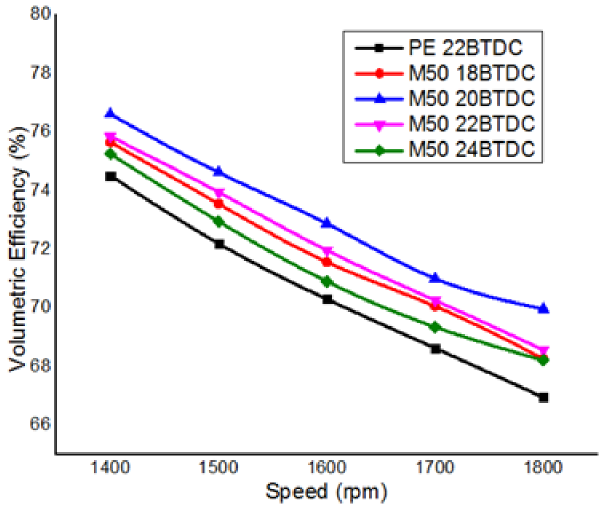


Figure 4.10 Variation of Volumetric efficiency of M50 fuel for different ignition timing

The engine speed (N) has a major effect on volumetric efficiency (Khidir and Atrooshi 2016). The volumetric efficiency is reduced with increasing engine speed. The increase of speed helps in increasing the mass flow rate, which is much higher than the drop caused by the decrease in volumetric efficiency. At higher engine speeds, the flow in some part of the intake process becomes chocked. Once chocked occurs, further increase of speed does not increase the flow rate significantly. Thus, the volumetric efficiency decreases sharply (Pulkrabek 2013).

Brake Power

The effect of ignition timing on brake power for the M50 fueled at WOT conditions is shown in Figure 4.11. The value of maximum power obtained with gasoline is 6.5 kW at 1800 rpm with CR 10:1, whereas the value of the maximum power output of M50 fuel is 6.01 kW at 1800 rpm. The engine power of M50 fuel is reduced by about 8% when compared to the power output of gasoline.

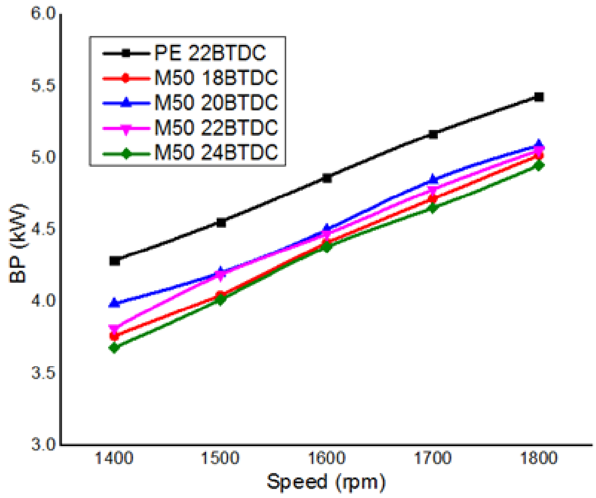


Figure 4.11 Variation of BP of M50 fuel for different ignition timing

It indicates methanol has a significant effect on the power output from the engine (Elfasakhany 2015). Methanol will ignite much less readily than gasoline. The heating value of methanol is lower than that of gasoline, and the heating value of the blended fuel decreases with the increase of the methanol content. As a result, lower power output is obtained (Iliev 2015).

Exhaust Emissions

The most common factor related to NO_x formation is temperature change (Balki et al. 2014). Topgül et al. (2006) and Yücesu et al. (2006) have explained that high octane numbered fuels advances the in-cylinder combustion, thus utilizes its large part of the heat for combustion and hence EGT of M50 decreases. Figure 4.12 b) clearly shows the reduction of NOx emissions for M50 fuel; the higher percentage of methanol in gasoline reduces the in-cylinder temperature. The reduction of temperature is due to the latent heat of the evaporation of methanol, which decreases the in-cylinder temperature when it vaporizes (Yanju et al. 2008). The effect of M50 fuel on HC emissions for different speeds is shown in Figure 4.12 a). The 50-volume percent of methanol addition to gasoline leads to oxygen enrichment and thus results in a reduction of NO_x and HC emission.

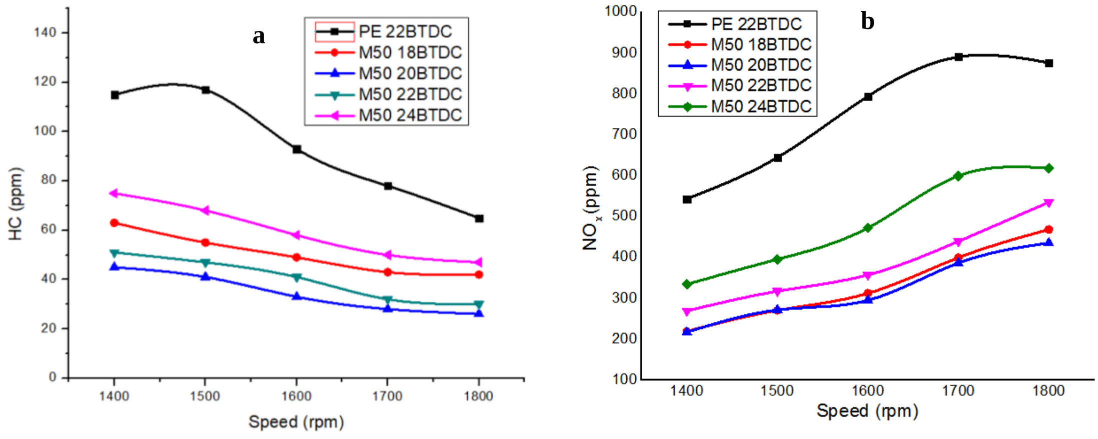


Figure 4.12 Comparison of a) HC and b) NO_x emissions between M50 blend and gasoline

The flammability limit and flame speed increases with Methanol addition result in improved combustion (Gong, Li, Chen, et al. 2019). Due to higher laminar flame speed, the flame front travels rapidly, and we obtain complete combustion inside a cylinder. Hence emissions due to incomplete combustion, such as HC, decreases significantly (Li et al. 2010).

It is known that CO emissions from internal combustion engines are controlled primarily by the A/F ratio. As shown in Figure 4.13 a), both temperature and fuel blends have a significant effect on CO emissions (Çelik et al. 2011). The higher oxygen contained in blended fuels and better mixing obtained under high temperatures (Canakci et al. 2013), due to the presence of oxygen in the molecular structure is enough for the formation of CO_2.

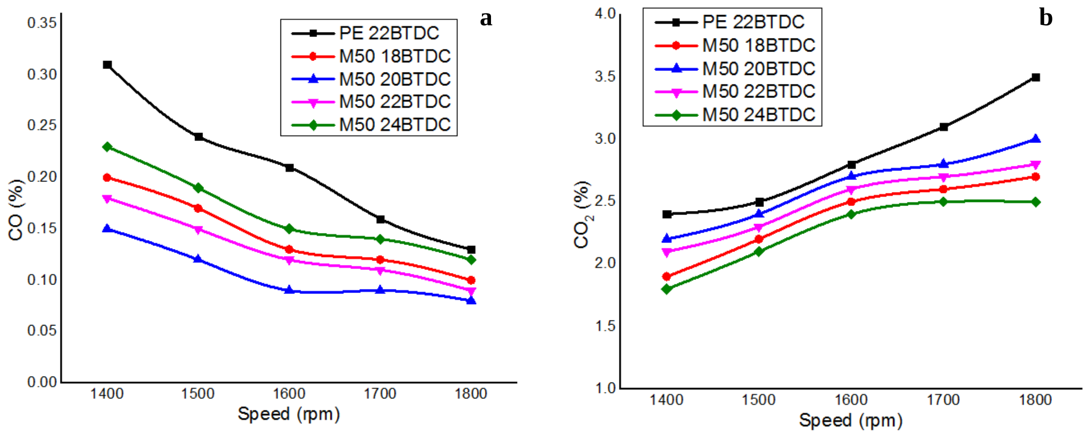


Figure 4.13 Comparison of a) CO and b) CO_2 emissions between M50 blend and gasoline

Hence results show lower CO emission. When CO_2 is concerned, the Hydrogen-carbon ratio of fuel plays a vital role in combustion. In the present case, the reduction of CO_2 attributes to the lower carbon content of methanol compared to gasoline. Figure 4.13 b) presents the comparison of CO_2 emissions of gasoline fuel with M50 fuel operating at different ignition timing.

4.3 Study of Performance, Combustion and Emission Characteristics of SI Engine fueled with Neat Methanol

The oxygenated fuel with good burning characteristics is always the right choice for SI engines. In this section, SI engine fueled with neat methanol fuel and the effect of varying compression ratio and ignition timings on performance, combustion, and emission characteristics was studied and optimized for better performance. Initially, this section provides details on the effect of change of compression ratio on the performance, emission, and combustion characteristics of the SI engine fueled with neat methanol. The experimentation was conducted for four different compression ratios (11,12,13 and 14) for a different speed range of 1400 rpm to 1800 rpm, ignition timing was kept constant at 22° BTDC, and the engine operated with WOT condition. Further, the experimental trials were carried out at WOT condition and compression ratio (CR14), using neat methanol. Ignition timing was varied from 18° BTDC to 26° BTDC with a 2° crank angle difference.

4.3.1 The effect of varying compression ratio: Combustion characteristic

Figure 4.14 presents the in-cylinder pressure variation for three different speeds for neat methanol operation. It showed a steep rise in in-cylinder pressure without indication of knock when engine was operated with methanol fuel with CR14. The pressure values obtained for different speeds with varying compression ratios suggest that higher CR improves fuel/air proportion in the cylinder and creates turbulence inside the cylinder, resulting in increased cylinder pressure and burning speed(Gong, Liu, et al. 2016).

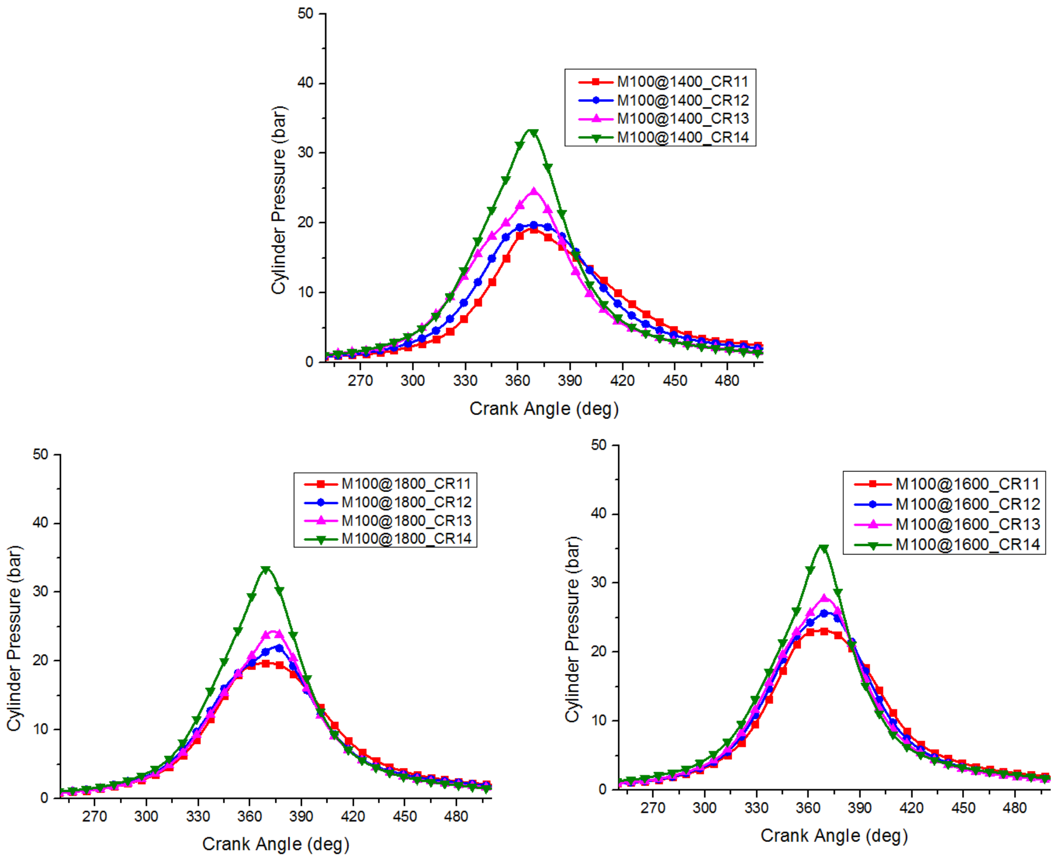


Figure 4.14 Variation of Cylinder Pressure with the crank angle for different compression ratios at different engine speeds

When the CR decreases, both the cylinder pressure and temperature decrease, and the ignition delay becomes more prolonged; thus, the combustion process is prolonged to expansion stroke. The CR11 and CR12 have a lower peak cylinder pressure and broad curve due to a longer combustion duration. The increased temperature during an expansion process; because of heat losses become more significant, and the brake thermal efficiency decreases(Roberts 2002).

The higher CR aided for adequate combustion and the raise of in-cylinder pressure and temperature. The temperature rise inside the cylinder accelerates the oxidation reactions of fuels, thereby speeding chemical reactions. In conclusion, a high heat release will occur, increasing the in-cylinder pressures and temperatures(Calam et al. 2019). Since Methanol fuel has a higher resistance to knock due to its octane number, it leads to maximum in-cylinder pressure at later crank angles (compared to gasoline fuel) under the same experimental conditions. Increasing speed increases the in-cylinder temperature with a slightly richer mixture present, which increases the peak pressure and shifts towards TDC. The CR14 has a peak pressure of 33.2 bar compared to 18.9 bar of CR 11 at 1400 rpm. However, at 1500 rpm, it increased to 36.3 bar for CR14 and 20.0 bar for CR 11. This increasing trend continues for 1600 rpm for CR11, CR12, and CR13, reaching 23.2 bar, 25.1 bar, and 27 bar, respectively, but for CR 14, the peak pressure falls to 35.1 bar. Whereas with the increase of speed to 1700 rpm and 1800 rpm, the peak pressure drops due to faster combustion cycles and insufficient time. For CR 11, the peak pressure is almost static within a relatively small range, diminishing the effect of engine speed.

4.3.2 The effect of varying compression ratio: Performance characteristic

Brake Thermal Efficiency

Higher CR is necessary for an increase of theoretical thermal efficiency and, at the same time, shortens the ignition delay because of the rise in-cylinder pressure and temperature at the time of fuel injection. Figure 4.15, it is observed that the increase of CR from 11 to 14 raises the in-cylinder temperature, thereby improving fuel vaporization. Once homogeneity of the mixture is achieved, the thermal efficiency shows better results. The highest thermal efficiency of 27.8% obtained at engine speed 1500 rpm with CR14, were as the brake thermal efficiency decreases for CR13, CR12, and CR11 with values 26.1%, 22.8%, and 20.01% respectively. However, BTE falls with respect to speed; after 1500 rpm, the time available is not enough for the combustion to complete, and reduced volumetric efficiency leads to a rich mixture; hence the thermal efficiency starts decreasing.

Verhelst et al. 2019 reported a decrease in compression work to have a positive effect on thermal efficiency. It is because the high specific heat capacity of the methanol results in more isothermal compression.

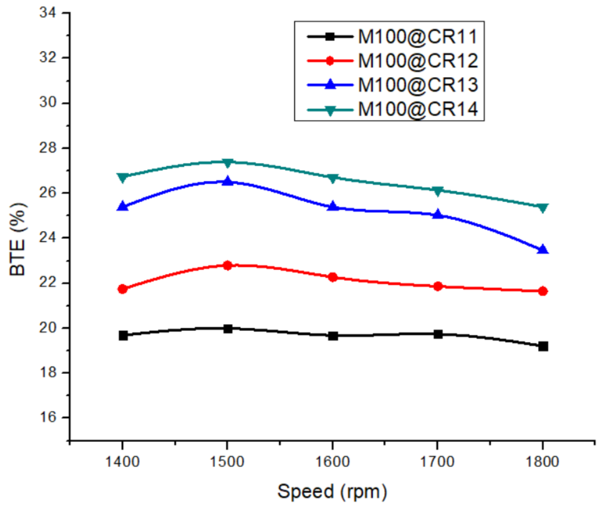


Figure 4.15 Effect of varying Compression ratio on BTE at WOT operating condition

During the compression stroke, the high latent heat of the vaporization of methanol allows the combustion mixture to absorb more heat from the cylinder. Hence, the work required to compress the mixture is less, which consequently improves thermal efficiency (Masum et al. 2015b). It is verified from the above that the brake thermal efficiency first rises at the beginning, then reaches the maximal value for optimal CR value and then subsequently declines. A probable cause is that at a lower speed, WOT conditions, the available time for any stroke is more; hence heat dissipation to the components and cooling media would be more too. The heat loss inhibits cylinder temperature and pressure to increase at the end of the compression stroke; this results in less work output per unit cycle.

Brake Specific Fuel Consumption

A lower Brake Specific Fuel Consumption means you are getting more work out of each drop of fuel. In short, an engine is more efficient at converting fuel to work at a higher load for the same speed because less of the fuel going into the engine is being used to heat the engine or escape into the exhaust. Figure 4.16 presents the effect of different compression ratios on brake specific fuel consumption with neat methanol operation. From the plots, it is revealed that an engine speed of 1500 rpm and CR 14, a minimum value of BSFC of 0.5678 kg/kW-hr, is obtained. The following lower compression ratios exhibit higher BSFC values of 0.597 at CR13, 0.678 at CR12, and 0.773 at CR11. The lowest CR shows a 26.5 % increase in BSFC compared to CR14 at 1500 rpm.

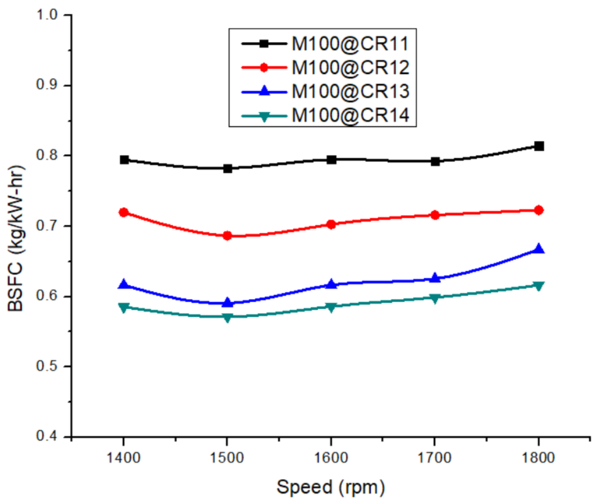


Figure 4.16 Effect of varying Compression ratio on BSFC at WOT operating Condition

The results obtained from plots clearly show that increasing the compression ratio causes a decrease in fuel consumption, whereas increasing the engine speed results in increased fuel consumption. The increasing speed reduces the available time for a cycle, which reduces the heat dissipation and increases the in-cylinder temperature and pressure. The volumetric efficiency decreases as well, leading to attain a stoichiometric air-fuel ratio, so thermal efficiency increases and followed by a reduction of BSFC.

Volumetric Efficiency

Figure 4.17 presents the effect of CR change on volumetric efficiency at varying speeds. The volumetric efficiency increases with increasing CR but reduces with increasing speed. The longer stroke duration and low cylinder pressure restrict the expansion of RGF, which increases volumetric efficiency. The maximum volumetric efficiency obtained is 77% at 1400 rpm for CR14. Increasing the CR reduces the quantity of RGF, thereby improving volumetric efficiency. The result of higher volumetric efficiency with methanol operation is mainly due to the combined effect of high latent heat of vaporization and low stoichiometric air/fuel ratio, which causes intake charge cooling during fuel evaporation (Verhelst et al. 2019). The charge cooling increases the intake charge density, thereby giving higher volumetric efficiency and also reduces the knock tendency in the engine.

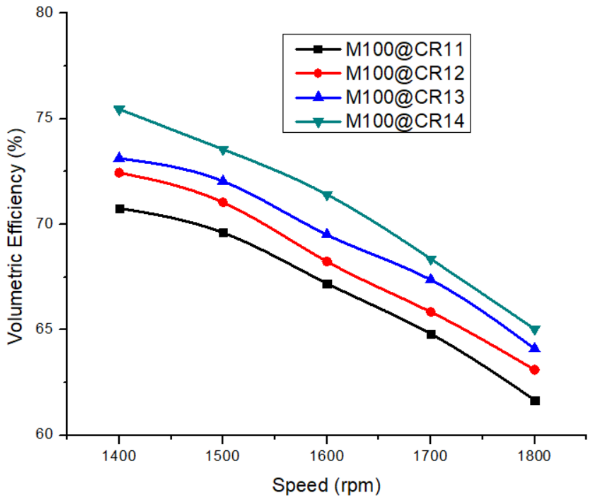


Figure 4.17 Effect of varying Compression ratio on volumetric efficiency at WOT operating condition

Brake Power

Figure 4.18 shows that the engine power would increase with increasing speed. The work supplied directly corresponds to engine power output; thus, increasing CR generates more power.

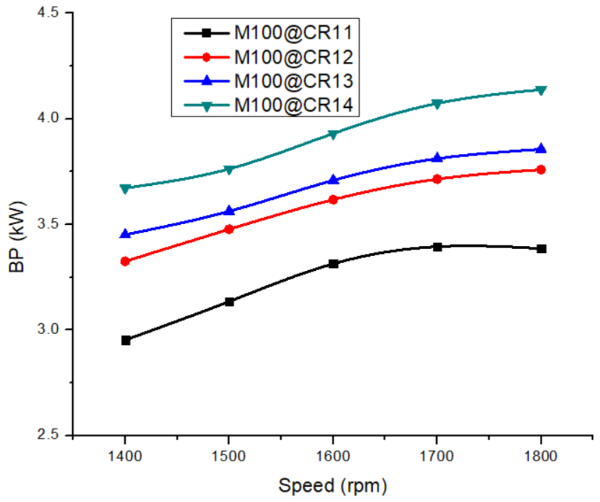


Figure 4.18 Effect of varying Compression ratio on BP at WOT operating Condition

From the figure, it is observed that CR 14 exhibits higher power output of 4kW at 1800 rpm, the power obtained with CR 14 is 21% more than the power output of CR11, which is 3.15 kW. However, increasing the compression ratio, engine power, and torque can be improved without knock occurrence (Gravalos et al. 2011). The knock resistance of methanol allows the engine to operate at a higher compression ratio.

4.3.3 The effect of varying compression ratio: Emission Characteristic

Figure 4.19 shows the variation of CO emission at different speeds. It is observed that CO emissions decrease with the increase of CR; CO emissions depend on the completion of combustion (Çelik et al. 2011). With lower CR, the heat is dissipated to the cylinder wall and cooling media. Also, a large amount of heat is consumed for the atomization of fuel, which results in lower cylinder temperature and higher volumetric efficiency. Figure 4.19 shows that CO emission has reduced substantially by 40% to 60 % with higher CR. Increasing CR increases the cylinder temperature and pressure, which are the favorable condition for combustion, results in decreased CO.

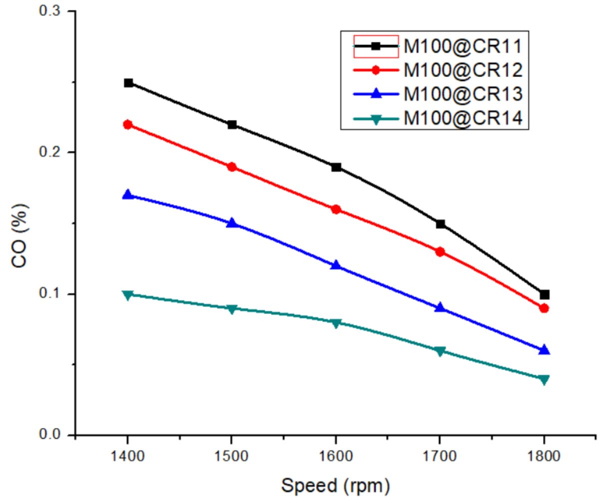


Figure 4.19 Effect of varying Compression ratio on CO emission at WOT operating Condition

The CO_2 emissions are opposite to the CO emissions for any speed concerning CR variation, as shown in Figure 4.20. Higher CR resulted in better combustion and improved CO_2 emission. However, comparing a particular CR for different speeds, the story is entirely different; the increasing speed increases with the amount of fuel inlet, resulting in a relatively rich mixture and so the formation of CO_2 (Alexandru et al. 2017). The reduction of CO_2 observed between CR11 and CR14 is nearly 14.2 %.

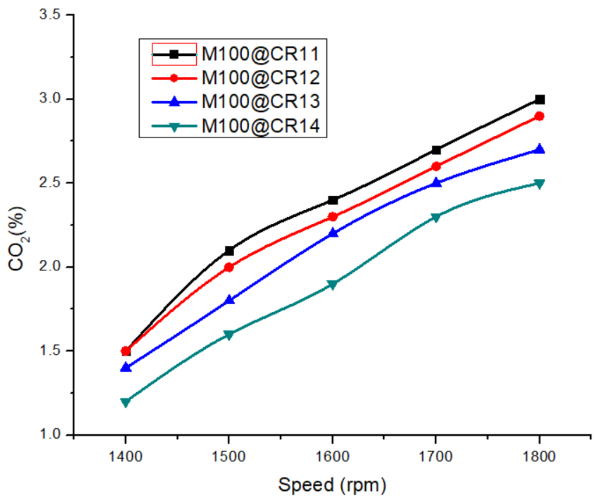


Figure 4.20 Effect of varying Compression ratio on CO_2 emission at WOT operating Condition

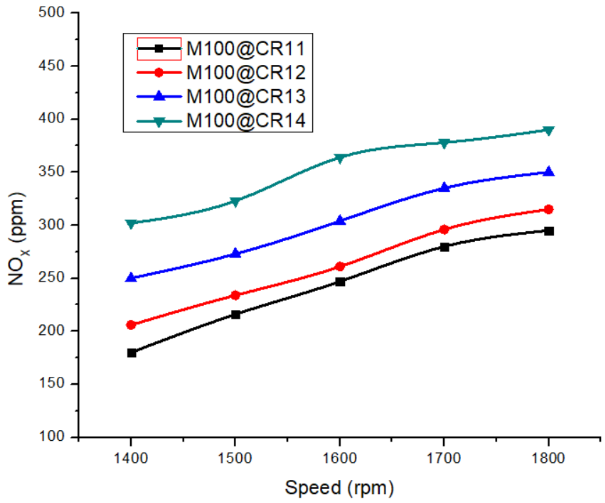


Figure 4.21 Effect of varying Compression ratio on NO_X emission at WOT operating Condition

Figure 4.21, shows that the variation of NO_x emission is observed and increases with an increase in CR and speed; the formation of NO_x depends on the cylinder temperature and oxygen availability. Increasing CR increases the cylinder pressure and temperature, which is a favorable condition for combustion and increases the peak temperature(Abdu and Inambao 2018). However, the increase in speed also has a similar impact on the NO_x emission. Higher speed provides less chance for the cylinder to get cool and which increases cylinder temperature. Though for the top speed of 1800 rpm, CO_2 emission is more, which is the result of excess fuel provided, the amount of fuel burnt per unit time is more and so as the temperature, resulting in higher NO_x emission.

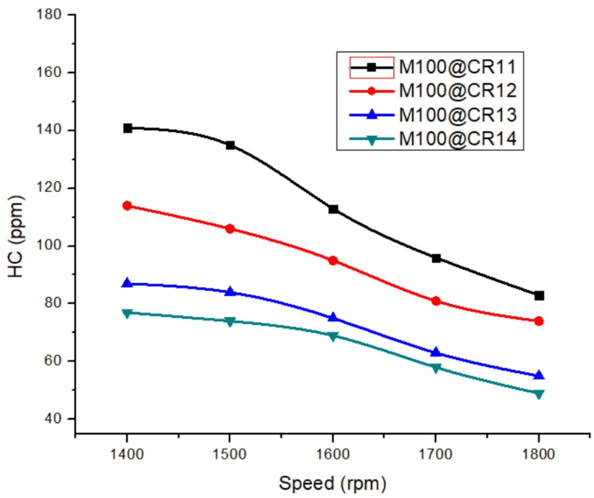


Figure 4.22 Effect of varying Compression ratio on HC emission at WOT operating Condition

Oxygen-enriched fuels account for reduced HC. It is observed from Figure 4.22 that HC emission decreases as the CR increased; a possible cause is just the higher cylinder pressure and temperature being favorable for combustion. The higher CR improves the post combustion oxidation, due to the increase in combustion temperature. It is observed that at low-speed, M100 finds slight difficulty in combustion due to its high latent heat. HC decreases with speed, probably due to improving the favorable condition for combustion.

4.3.4 The effect of varying ignition timing: Combustion characteristics

Higher in-cylinder temperature and pressure, along with a slightly richer mixture of neat methanol, increases the peak pressure, and it shifts the peak towards TDC. Figure 4.23 shows that the maximum cylinder pressure of 34.7 bar is observed at 20° BTDC followed by 30.2 bar at 22° BTDC. The 20° BTDC maximizes pressure due to the relatively improved homogeneous mixture due to higher pressure and temperature.

In this parametric study, it was observed that the combustion characteristics of neat methanol operation is matched with combustion characteristics of gasoline-fueled SI engine results when operating at higher compression ratio and optimal ignition timing.

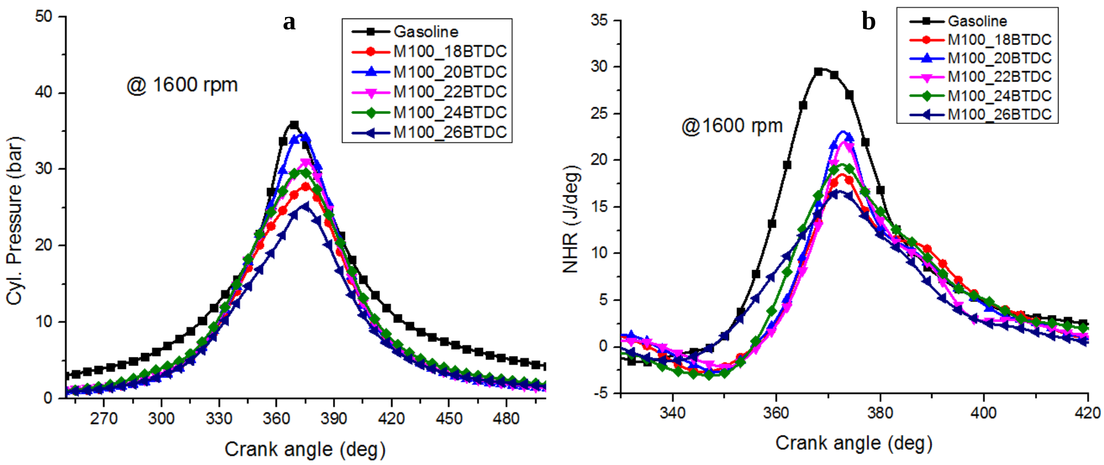


Figure 4.23 Variation of Cylinder Pressure versus crank angle for neat Methanol with different ignition timing

The engine speed of 1600 rpm has good air-flow motion and increased flame-propagation speed, which improves the combustion efficiency, thereby increasing cylinder pressure correspondingly. Methanol with the higher latent heat of vaporization requires slightly more time for the absorption of heat during the vaporization in the compression stroke, so retarding the ignition timing for methanol operation would assist it in burning more efficiently.

4.3.5 The effect of varying ignition timing: Performance characteristics

Brake Thermal Efficiency

The performance evaluation is majorly based on the energy conversion efficiency of fuel. In this section, the effect of ignition timing (18°-26° BTDC) on BTE was studied and results were compared with baseline fuel. Higher CR and shortened Ignition delay are the ideal characteristics for good thermal efficiency(Roberts 2002). Ignition delay is the crank angle span between the start of burning and 10% mass fraction burnt. In this case, after carefully estimating the delay period for the late start or early start of ignition, the best-suited ignition timing is selected where the thermal efficiency obtained is maximum compared to other timings. The high flame velocity of methanol improves the combustion rate. It raises the power output on account of the increase in thermal efficiency despite its higher latent heat of vaporization and poor lean burning characteristics.

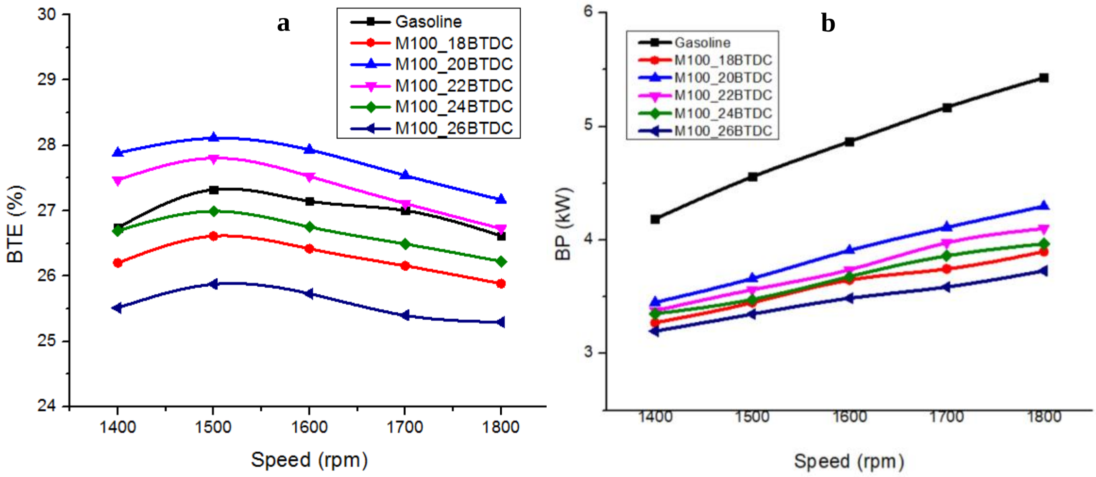


Figure 4.24 Effect of varying ignition time on a) BTE and b) BP for different speeds

Figure 4.24 a) shows that gasoline and methanol efficiency characteristics indicate that the burning of methanol at 20° BTDC crank angle results in better conversion of the chemical energy into mechanical work compared to gasoline. Therefore, the best combustion and maximum pressure in the cylinder were observed at this ignition timing value. The highest efficiency of 28.1% is observed with neat methanol 20° BTDC crank angle, whereas least 25.7% was seen for 26° BTDC crank angle. Over advancing the ignition timing has caused early combustion, which affects the compression cycle, thereby reducing the power output and thermal efficiency.

Brake Power

Figure 4.24 b) shows the variation of brake power output with the different spark timings. The performance comparison between gasoline and neat methanol in terms of power produced suggests the differences in fuel characteristics of the two fuels. Methanol with lower energy content has a lower power output compared to gasoline. In this present case, neat methanol is operated with a higher compression ratio, which actually has a significant impact on increased power output compared to lower CR, where the higher the compression ratio, the higher will be the cylinder pressure, which results in better work transfer to the moving piston thereby increasing the power. The peak brake power of 4 kW was observed, at 1800 rpm engine speed and ignition timing of 20° BTDC crank angle. The brake power is increased with the increase in speeds; at higher speeds, the flow-induced turbulence is more, and it helps with better air-fuel mixture composition and aids for better flame propagation, so that power output is more. With the traits mentioned earlier, the ideal selection of ignition timing would additionally compensate for the overall improvement in power output. Over advancing the ignition timing (26° BTDC) might cause early combustion and more fraction of fuel burns before the piston reaches TDC. Hence advancement is reduced from 26° BTDC to 18° BTDC with the decrement of 2° crank angle. The ignition timing less than 20° BTDC crank angle has shown a decreasing trend in power; due to the late burning of fuel fraction in the expansion stroke, the work transfer to the piston is lost.

Volumetric Efficiency

The amount of air inducted to the cylinder depends on the suction pressure, valve timing, RGF, and the inlet temperature of the air. In the present case, neat methanol operation requires higher CR, which reduces the RGF retention in the cylinder and charge cooling effect due to the high latent heat of vaporization, which improves the volumetric efficiency. Figure 4.25a) presents the volumetric efficiency of neat methanol with different ignition timing at different speeds. The maximum volumetric efficiency obtained is 76% at 1400 rpm for ignition timing 20° BTDC crank angle.

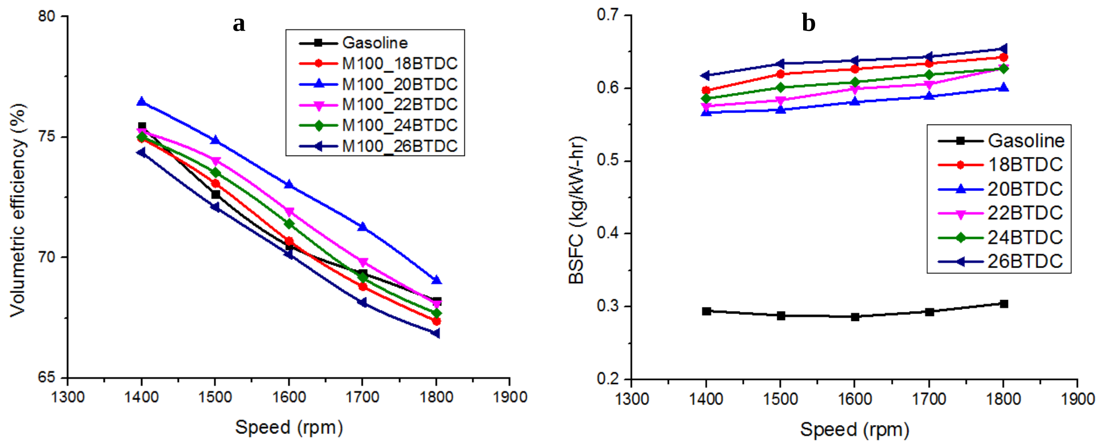


Figure 4.25 Effect of varying ignition time on Volumetric efficiency and BSFC for different speeds

The charge cooling increases the intake charge density, thereby giving higher volumetric efficiency and reducing the engine's knock tendency. Volumetric efficiency decreases with an increase in speed. Advancing the ignition timing improves the volumetric efficiency for the higher speed, where sufficient time is available for the combustible mixture to burn completely. There is not much of a change in volumetric efficiency is observed with the ignition timing change. The variations with cylinder pressure and temperature directly affect the combustion characteristics and have shown better results for optimized ignition timing.

Brake Specific Fuel Consumption

Figure 4.25b) shows the relation between BSFC and the ignition timing for different engine speeds. The lower energy content fuel is always susceptible to an increase in specific fuel consumption, as it requires more fuel to be burnt to produce the energy needed. The BSFC value of methanol fuel with un-optimized ignition timing is double the gasoline fuel value, whereas, with the optimized timing, we can reduce the difference by 5 %. As the energy content remains constant for all the ignition timing, the correct ignition timing will helps in improvised consumption. In the present case, experimental trials were conducted for the WOT condition. At higher engine loads, the higher rate of fuel-air charge is inducted into the cylinder to accommodate the rise in brake power required to overcome the load applied to result in faster completion of the combustion cycle. For ignition timing 20° BTDC the BSFC values obtained was 0.527 kg/kW-hr at 1500 rpm, least compared to other timings. Over advancing to 26 BTDC has a higher BSFC value of 0.612 kg/kW-hr at 1500 rpm. The figure presented above reveals that 20° and 22° BTDC ignition timing has the least BSFC value of 0.557 kg/kW-hr and 0.573 kg/kW-hr for M100 fuel at 1500 rpm, the least value of 0.612 kg/kW-hr is obtained for 26° BTDC at 1500 rpm due to over advancing the ignition timing. The optimized ignition time at which a better conversion of energy takes place, along with extra oxygen molecules, ensures the completeness of combustion, resulting in lower fuel consumption.

4.3.6 The effect of varying ignition timing: Emission characteristics

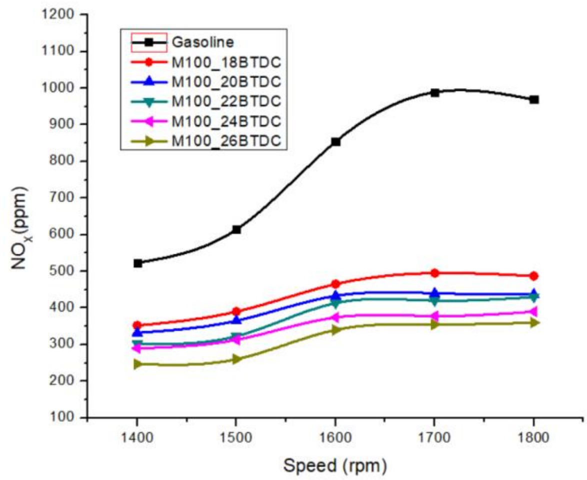


Figure 4.26 Variation of NO_x emissions of M100 with a different ignition time

The low carbon composition of methanol is expected to produce fewer oxides of carbon. In addition to this, other chemical properties such as high latent heat of vaporization would reduce the in-cylinder temperature, and it directly reflects the reduction of NO_x emissions. In this section, the focus is on obtaining the correct ignition timing, where the exhaust emission is observed to be the least because of its good burning characteristics.

The Operating SI engine with neat methanol has shown a considerable reduction in NO_x formation. The exhaust NO_x emissions obtained with neat methanol for different ignition timing with varying engine speed is shown in Figure 4.26.

The baseline fuel, gasoline, has shown high NO_x when compared to neat methanol fuel, which is reasonably due to high combustion temperature. The lower heating value of the methanol fuel is believed to have produced lower gas temperatures inside the cylinder during the combustion process resulting in lower NO_x emissions since the NO_x emission is majorly prompt or thermal NO_x. A maximum NO_x reduction of 50%-60% of NO_x emission is observed for higher speeds, whereas at lower speed reduction percentage varies from 30%-40%. The results indicate that the excellent burning characteristics with the optimized ignition timing have a marginal increase in NOx level among the methanol operated, mainly due to the rise in pressure and temperature inside the cylinder. Engine running at higher CR may account for an increased NO_x level. Still, the cooling effect due to higher latent heat of vaporization of methanol will always have control over the NO_x formation.

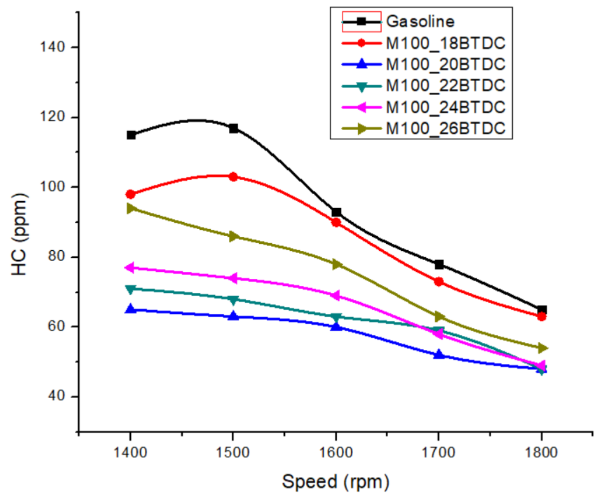


Figure 4.27 Variation of HC emissions of M100 with a different ignition time

The effect of ignition timing on HC emission for different speed variations is as shown in Figure 4.27. From the plots, it is clear that there is a reduction of HC emission level with the increase of engine speed. The least value is obtained with Ignition timing of 20° BTDC, which is reflected for all the exhaust gases.

The reason behind the resulting reduction in HC emissions is due to variation in exhaust temperature caused by changing ignition timing at different engine speeds. The wide flammable limits and higher flame propagation speed avoid slow-burning of methanol charge in the cylinder, which is a clear sign of improved combustion characteristics of the engine.

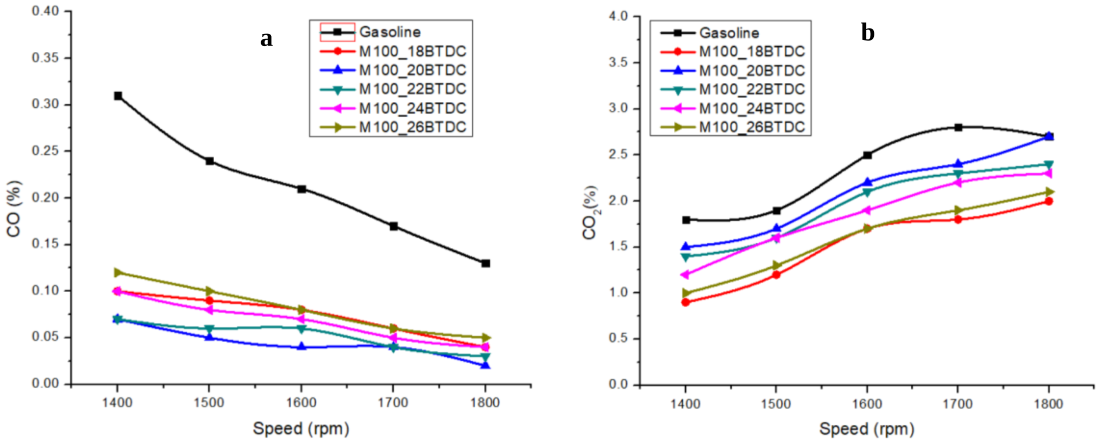


Figure 4.28 Variation of a) CO and b) CO_2 emissions of M100 with a different ignition time

CO emission is due to partial combustion caused by insufficient air while fuel burning or can be a wrong selection of operating parameters that affect the combustion. Ignition timing plays a major role in combustion, which in turn might reflect on exhaust emissions as well. The early advancement of late ignition might always result in loss of chemical energy in terms of CO and HC emissions. Figure 4.28a) shows the variation of CO emissions of neat methanol at different ignition timings and varying engine speed. A significant reduction in CO is observed with overall speed variation, the enhanced oxygen content has caused a leaning effect during combustion, and hence CO emissions have reduced sharply. It is noticed that the lower CO emissions are obtained at 20° BTDC ignition timing for all the engine speeds. The CO reduces with the increase in speed, and the percentage emission reduction found was between 50% - 60%. The higher flame speed and the smaller combustion cycle at the higher speed exhibits the least CO emission.

Carbon dioxide is non-toxic but contributes to the greenhouse effect. At different ignition timing, the CO_2 values of methanol are shown lower than gasoline; because alcohols have both a lower C/H ratio and low carbon content than gasoline. Figure 4.28 b) shows the carbon dioxide emissions for neat methanol operation at different ignition timing. In the present investigation, CO_2 tends to increase with speed, and later, it begins to fall for higher speed; the reason behind this is due to variation in combustion duration with each speed. The higher oxidation rate of carbon to CO_2 is caused due to the presence of additional oxygen in the methanol. The effect of ignition timing on the CO_2 emission is, as shown in the figure suggests, 20° BTDC advancement is best suited for the neat methanol operation. CO_2 emission is a reflection of combustion completion, and the trend will always be opposite to CO emission.

4.4 Study of Performance, Combustion and Emission characteristics of Hydrogen enriched neat Methanol fuelled SI Engine

4.4.1 Effect of Hydrogen Enrichment: Combustion Characteristics

Cylinder Pressure variation

Variation of in-cylinder pressure for different methanol/hydrogen fuels at different speeds is as shown in Figure 4.29. The peak pressure of gasoline is found slightly higher than neat methanol at all the speeds. However, the peak pressure was found relatively away from the TDC for gasoline (also represented in Figure 4.30) (Gong, Li, Chen, et al. 2019). In-cylinder temperature rise is low at lower speeds for neat methanol operation, where it finds it difficult to burn due to its high latent heat of vaporization. Another chemical property restricts the peak pressure of methanol fuel; methanol's heat content is almost half the heat content of gasoline. However, relatively high flame velocity shortens the combustion duration, results in an early peak pressure occurrence near the TDC. At 1400rpm, the peak pressure for methanol is 8.5% lower than gasoline. The rising speed, maintaining a relatively high in-cylinder temperature, helps in the combustion of methanol, but the low heating value restricts the peak pressure. At 1800rpm, M100 has recorded only a 1% peak pressure difference from gasoline. Whereas the position of peak pressure is shifted from 376° CA at 1400rpm to 372° CA at 1800rpm when compared to gasoline-fueled engine operation, it was 379° CA at 1400rpm and 377° CA at 1800rpm.

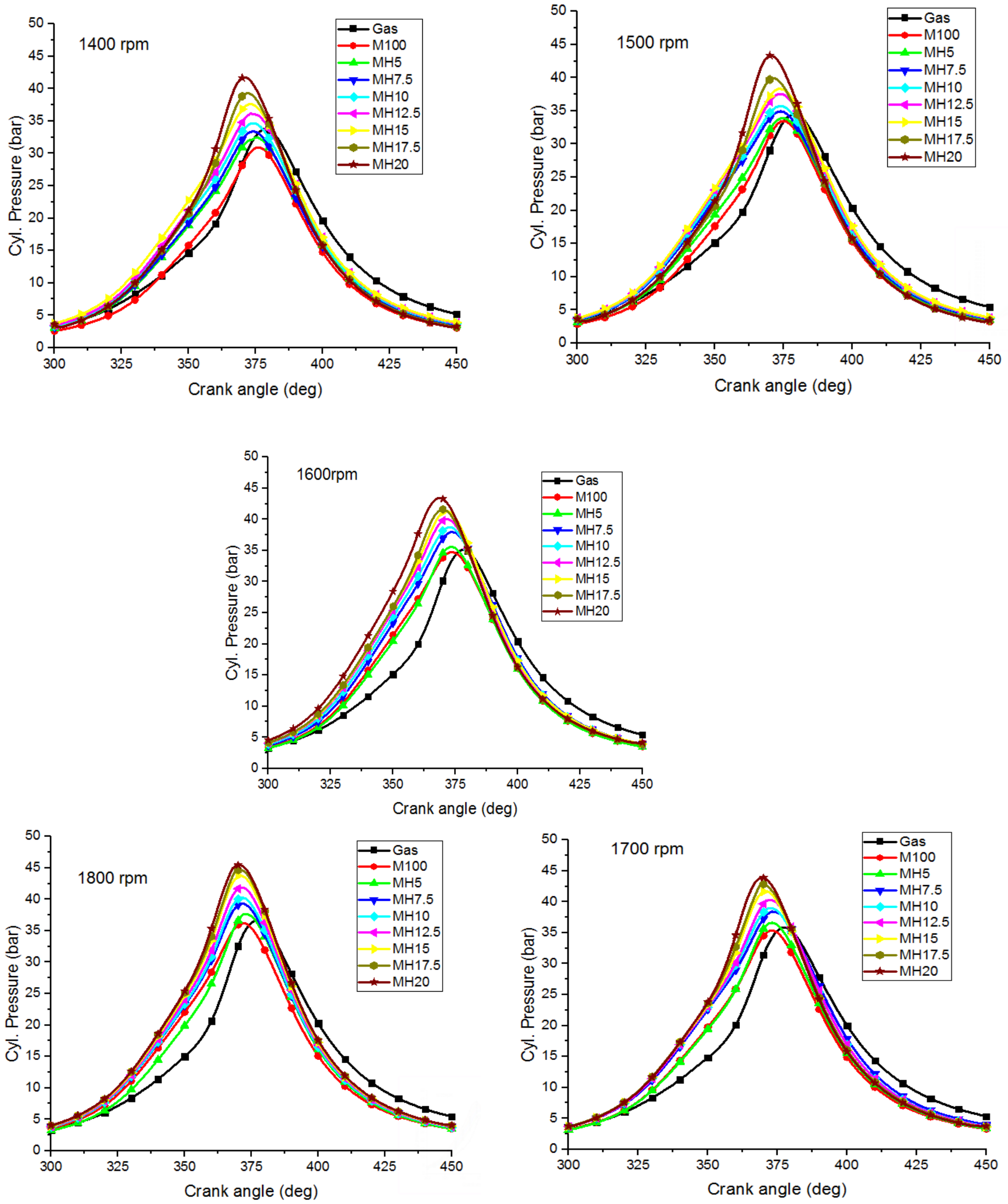


Figure 4.29 Variation of cylinder pressure for different fuels at different speeds

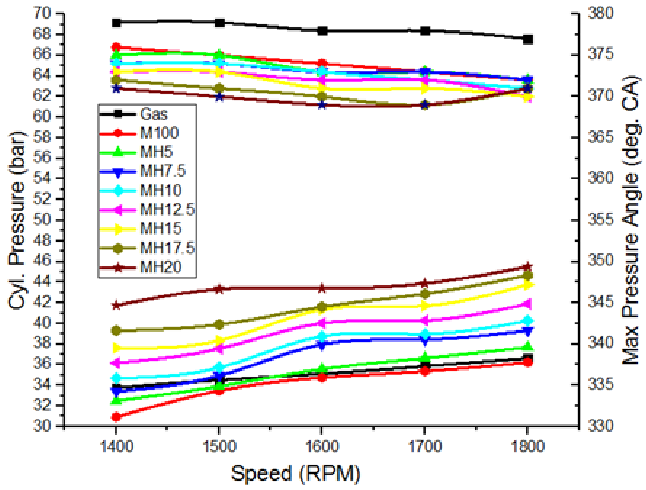


Figure 4.30 Variation of Maximum Cylinder Pressure and variation of the position of maximum cylinder pressure with speed for different fuel

Hydrogen enrichment is found helpful in the combustion of methanol because of the high flame speed and high energy content. At the same speed of 1400rpm, M100 has 8.5% lesser peak pressure than gasoline, MH5 3.7% less than gasoline. Increasing the hydrogen percentage further increases the peak pressure; MH10 has recorded a 2.7% rise at 1400rpm from gasoline, while MH20 has a 23.7% rise from gasoline at the same speed. The peak pressure occurrence has also shifted towards TDC, as for MH5, the position of the peak pressure at 1400rpm is recorded at 375° CA. At 1800rpm, even MH5 has almost 3% higher peak pressure than gasoline, which clearly shows the ability of fast-burning of hydrogen. An overall 0.2% for MH5 to 24% for MH20 rise in peak pressure than gasoline is observed. However, the rate of peak pressure rise is observed to fall slightly at higher speeds of 1700rpm and 1800rpm for MH17.5 and MH20. The probable cause for it may be the restriction in the methanol combustion as the concentration of hydrogen in the air-fuel mixture is high, and due to the high diffusivity of hydrogen, it surrounds available oxygen, and hence it is difficult for the methanol molecules to reach oxygen. The position of peak pressure is also shifted from 370° CA of MH15 to 371° CA for MH17.5 and MH20.

4.4.2 Effect of Hydrogen Enrichment: Performance Characteristics

Brake Power

Figure 4.31, variation of brake power for hydrogen enriched neat methanol fuel in SI engine. The brake power is reduced to a large extent near 20% after switching from gasoline to neat methanol due to the relatively low heating value of methanol. However, increasing the speed increases the fuel flow rate as the number of operating cycles is increased, hence, leading to increased brake power. It is observed that enriching methanol with hydrogen increases the total energy supplied by the fuel, therefore, increasing the brake power (Şöhret et al. 2019). However, properties of hydrogen such as high laminar flame speed, diffusivity, and adiabatic flame temperature enhance the combustion behavior and generate more engine power and thermal efficiency (Ji et al. 2013).

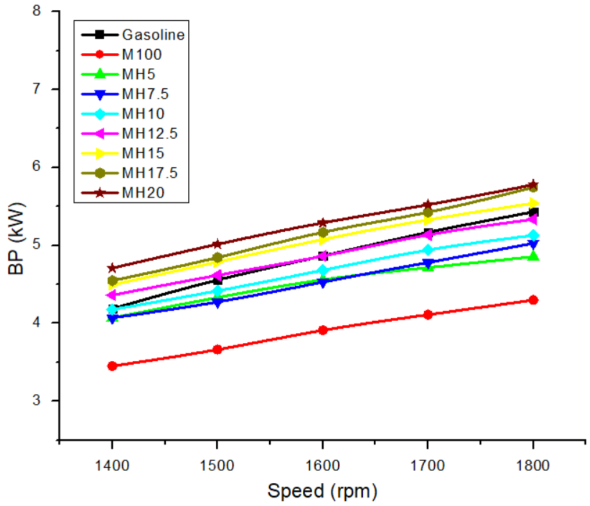


Figure 4.31 Variation of brake power with speed for various fuels.

In the present investigation with the 5% of hydrogen enrichment, the brake power has increased by 16% overall compared to neat methanol. Further enrichment till MH15, the brake power increment rate remains near to 3% to 3.5%, after MH15, the rate of increment started decreasing, probably due to relatively low volumetric efficiency.

Merely an average of a 1% increment of brake power was observed for MH20 from MH17.5. The overall increase in brake power is 6.75% between low speeds 1400-1500 rpm; similarly, for a high speed of 1800 rpm, the increment is by 4%. At 10% enrichment, the brake power is found near to the gasoline, which is all set to come by the better combustion properties of hydrogen.

Brake Thermal Efficiency

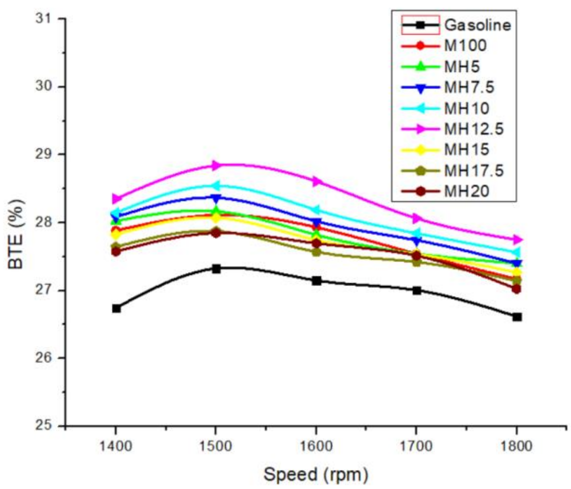


Figure 4.32 Brake Thermal Efficiency with speed for different fuels.

Methanol has better combustion quality respective to gasoline, which reflects in better brake thermal efficiency. At 1400 rpm, a 3.6% increase in BTE is observed for M100 and 2.5% increase for 1800rpm. Figure 4.32 refers to the BTE variation of hydrogen enriched neat methanol fueled in SI engine.

The BTE is increasing with speed first, and then it declines with higher speed, which depends upon the time available for completing the cycle, as it contributes to volume inducted as well as cooling of the engine. At low speed, the volume inducted is more, but the cooling of the cylinder is also more, which leads to low thermal efficiency, as in the case of 1400. However, at higher speed, the volume inducted is decreased due to the increase in residual gas fraction; the thermal efficiency is reduced too.

In the case of M100, the high latent heat cools the incoming air, making it difficult to raise the combustion chamber temperature to the desired level for combustion temperature at low speed. Increasing speed increases the combustion chamber temperature near to the desired level. Hence, BTE increased by 1.5% for 1500rpm and 0.7% for 1600rpm. However, a further increase in speed increases the temperature, but the volumetric efficiency falls rapidly. The laminar flame velocity of hydrogen is higher than other fuels, which helps it in fast combustion and low ignition energy also helps in early combustion. For a smaller amount of hydrogen enrichment, the BTE trend follows M100; as speed increases till 1600rpm, it is increasing, but for further increased speed, it decreases. For MH5, BTE increases by 0.6% compared to M100 followed with nearly 1.1 % increase for MH7.5 and MH10, the maximum raise ws observed in MH12.5 of 2.5%. It was found that hydrogen enrichment beyond MH12.5, the brake thermal efficiency decreases. The possible cause if due to the increase in charge specific heat because of the increased residual dilution and charge temperature, which in turn affect the brake thermal efficiency (Yousufuddin et al. 2008). This decrease may be due to the low volumetric efficiency in case of increasing hydrogen enrichment. Hence, BTE is decreased by 2.4% and 2.6 % for MH17.5 and MH20 respectively.

Volumetric Efficiency

The increase of volumetric efficiency by 10.25% for M100 from gasoline has shown a decreasing trend after hydrogen enrichment. For MH5 volumetric efficiency reduction observed is 1%; further, it continues to decrease with hydrogen percentage, and the rate of decrease is increasing even fast as for MH20; there is a reduction of nearly 3% from MH17.5 is observed. At 1800 rpm for MH20, it is even worse as it nears 5% decrease.

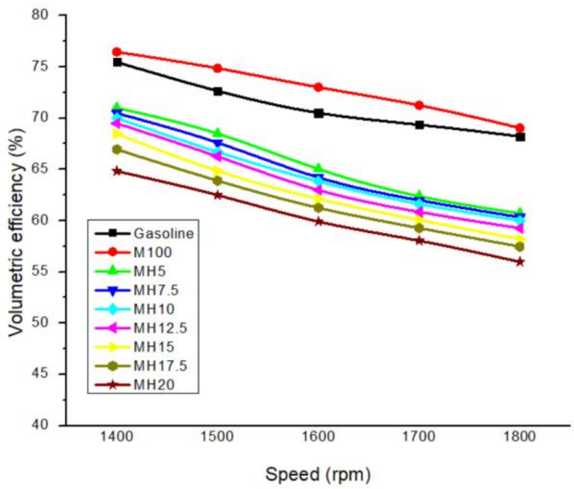


Figure 4.33 Variation in volumetric efficiency with speed for different fuels.

The volumetric efficiency is decreasing continuously with hydrogen enrichment due to the gaseous form of it as well as high diffusivity of it being responsible for displacing a large amount of air(Gong, Li, Yi, et al. 2019; Kak et al. 2015). At the higher speed, there is very little time available for residual gas to expand as well as for engine cooling, which contributes further to decreasing the volumetric efficiency. Figure 4.33, presents then variation of volumetric efficiency with respect to hydrogen enrichment neat methanol fuel and gasoline.

Brake Specific Energy Consumption

Figure 4.34, show the effect of hydrogen enrichment on the brake specific energy consumption of the neat methanol fueled engine at WOT condition. From the graph it is observed that, M100 has nearly 6.3% lower BSEC compared to gasoline. However, comparing BSEC values of hydrogen enriched fuels with M100 it was found that, the reduction percentage of nearly 1.4% and 2.3 % was found for MH10 and MH12.5. MH5 and MH7.5 almost shown the similar values compared to M100. But, for MH15, MH17.5 and MH20, increase of 1.25% and 2.5% in BSEC was observed, though it is less than gasoline even at low volumetric efficiency.

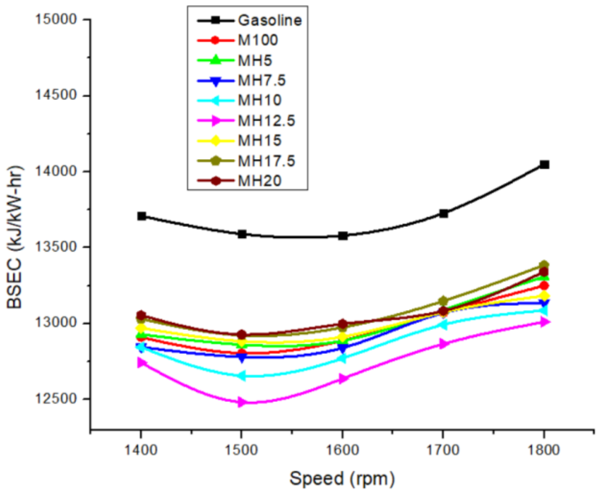


Figure 4.34 Variation in BSEC with speed for different fuels

The availability of the oxygen in the methanol and wide flammability limit of hydrogen may be the reason for the lower BSEC, resulting in complete combustion of fuel and increased engine power due to the increase in the amount of hydrogen fuel. Lower values of BSEC is observed for lean mixtures, it follows the required pattern of reduction till MH12.5. At lean condition the specific heat of burned gas decreases thereby increasing the effective value of specific heat ratio (Olalekan et al. 2017).Hence the significant amount of energy released from the fuel is transferred as work to the piston during expansion. However, for high hydrogen fractions beyond MH12.5, the BSEC value increases compared to M100 fuel. It gives an idea of hindrance in combustion due to the unavailability of sufficient air.

4.4.3 Effect of Hydrogen Enrichment: Emission Characteristics

The heat content of M100 is relatively very low, which is not allowing the cylinder temperature and working fluid temperature to rise more, which is reflected in exhaust gas temperature (EGT, Figure 4.35) and NO_X emission (Figure 4.36). On the other hand, methanol having oxygen atoms present needs less air for combustion. Hence, with even maximum injector open time, it burns under a relatively lean condition. Therefore, the temperature rise is further restricted.

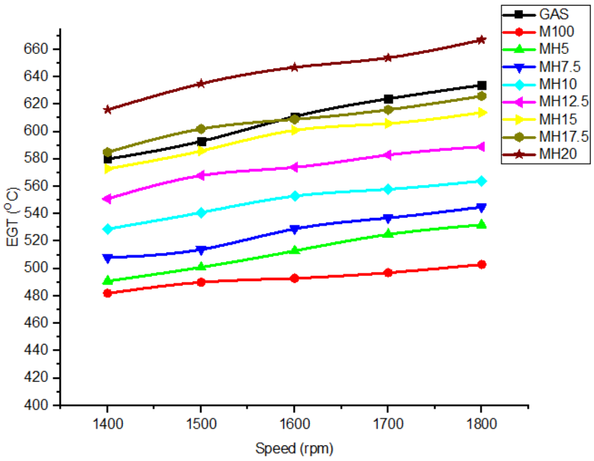


Figure 4.35 Variation of EGT with speed for various fuel

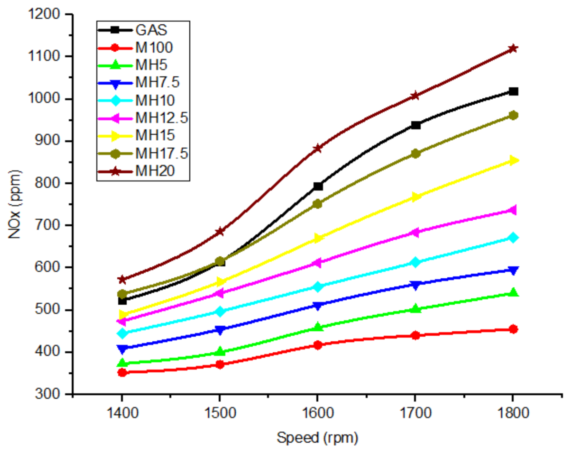


Figure 4.36 Variation of NO_X with speed for various fuel

At 1400rpm, M100 has 17% less EGT and 33% less NO_X formation from gasoline. With increasing speed, NO_X emission and EGT increases; however, because of heating value difference and air requirement, the increments for gasoline are more than M100. At high speed of 1800rpm, M100 has 20.67% less EGT and 53% less NO_X than gasoline. Hydrogen is considered to be favorable fuel for combustion because of it's properties like, high flame speed, minimum ignition energy requirement, and high adiabatic temperature and etc., These properties help in increasing the working temperature of working fluid, lead to increase EGT and NO_X (Kak et al. 2015; S. Wang et al. 2010). However, for low hydrogen enrichment, the total heating value is not meeting the gasoline level as well, as the conditions are incredibly lean, too, compare to gasoline. For MH5 operation at 1400rpm, there is a increase of 2.3% EGT and 10% increase in NO_X compared to M100 operation, but EGT fall of 15% and 29% and NO_X, respectively from gasoline is observed; nevertheless, at a high hydrogen concentration of MH20, at the same speed of 1400rpm, there's a 28% increment in EGT, and 62.5% increment in NO_X from M100 is observed. In comparison, 6.3% EGT and 9.3% NO_X increment from gasoline are observed. The rate of increase of EGT and NO_X with speed is increasing with hydrogen enrichment, similar to gasoline. For M100, an average 1% increment per 100rpm in EGT and 6.6% increment per 100rpm in NO_X against 2.25% in EGT and 17.5% in NO_X per 100rpm for gasoline is observed. With hydrogen enrichment, the increment per 100rpm for EGT varied from 2% for MH5 to 2.15% for MH20 and for NO_X, varied from 7% of MH5 to 18.58% of MH20.

Compared to M100, MH20 has seen a large deviation of 28% at 1400 rpm and 33% at 1800 rpm in EGT, while NO_X has increased extremely high as 62.5% at 1400rpm to 146.5% at 1800rpm. It has been observed that for MH20, the values of EGT and NO_X have crossed the emission level of gasoline. EGT is recorded average 6% higher, while NO_X is found an average 8.6% higher than gasoline. It can be noticed that the total heating value of MH20 is slightly below gasoline. From Figure 4.36, a sudden rise in the MH20 curve is observed after 1600rpm, probably due to the slight rich hydrogen mixture rapids up the flame propagation but late burning of methanol due to unreachability of it towards the air increases the exhaust gas temperature. It increases the average cycle temperature, leading to a favorable condition for NO_X formation.

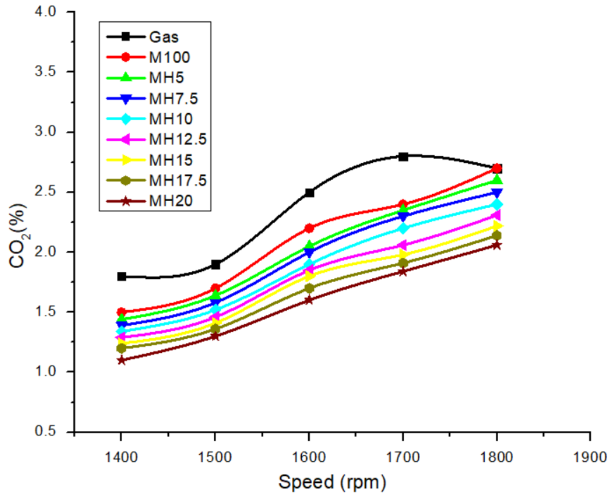


Figure 4.37 Variation of CO_2 emission with speed for various fuels

Gasoline has a C-H ratio more than methanol, which causes more CO_2 production during combustion. As the speed increases, the supply of fuel also increases but the volumetric efficiency decreases, which increases the carbon concentration in the exhaust gas. shows the variation of CO_2 emission in the exhaust gas. For gasoline, the emissions are highest, which increases rapidly with the increase in speed. However, methanol, with less C-H ratio, decreases the amount of CO_2 emission to a large extent despite an increase in fuel consumption by mass. Another probable cause behind it may be the extra lean operation of methanol, as it needs less air to burn, it operates on the relatively lean mixture at WOT conditions. At low-speed methanol has more reduction of CO_2 compared to gasoline than high speed, as 1400rpm has a 17.2% reduction.

The hydrogen enrichment process is mixing hydrogen in incoming air through a PFI injection system similar to M100. It replaces air and reduces volumetric efficiency, but, hydrogen being clean fuel, doesn't produce any CO_2. Hence, after hydrogen enrichment, the amount of CO_2 emission decreases (Yilmaz and Taştan 2018). However, the rate of CO_2 reduction is lowered with an increase in the amount of hydrogen enrichment. The percentage reduction of CO_2 observed for MH5 from M100 is 4.5% and compared to gasoline it is 18.6% at 1400rpm, respectively. Similarly, at 1800rpm, there is a reduction of 8.3% compared to gasoline was observed. However, compared to gasoline and M100, the reduction in CO_2 at higher hydrogen concentration is high. For MH20, the reduction rates from M100 are 29% at 1400rpm and 42.73% at

1800rpm, while from gasoline, 58.9% at 1400rm and 42,73% at 1800rpm. Figure 4.37 gives the details of CO emission variation for gasoline, methanol, and hydrogen-enriched methanol.

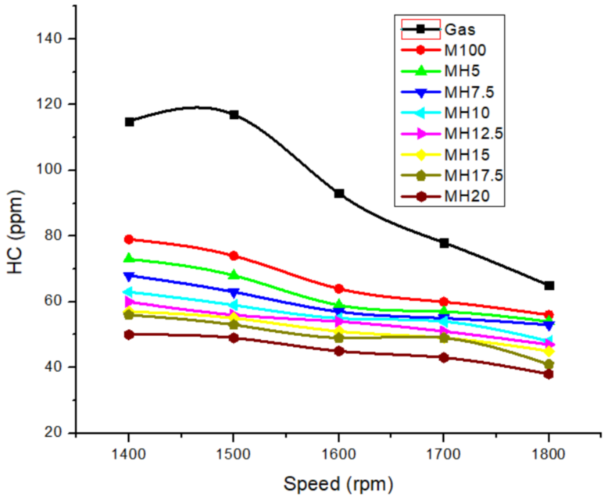


Figure 4.38 Variation of HC emission with speed for various fuels

A similar case is observed for HC and CO emissions. Methanol fueled SI engine produce lower HC emissions as well as CO emissions due to its less C-H ration as well as high burning capabilities. CO and HC emissions with respect to gasoline, are always higher than the rest of the fuels at all the speeds. While M100 fuel at 1400rpm has HC, emissions reduced by 30.4% and at 1800rpm difference of 14.4% was observed. It is observed that at low-speed, M100 finds slight difficulty in combustion due to its high latent heat. Hence, the HC emission reduction rate is lower compared to the higher speeds. However, hydrogen can burn fast, reduces HC emissions further. For MH5, the HC emission is reduced by 8.1% overall from M100 and 36.3% from gasoline, while for MH20, it is reduced by 38.9% overall from M100 and 57.9% overall from gasoline. Figure 4.38 gives the details of HC emission variation for gasoline, methanol, and hydrogen-enriched methanol.

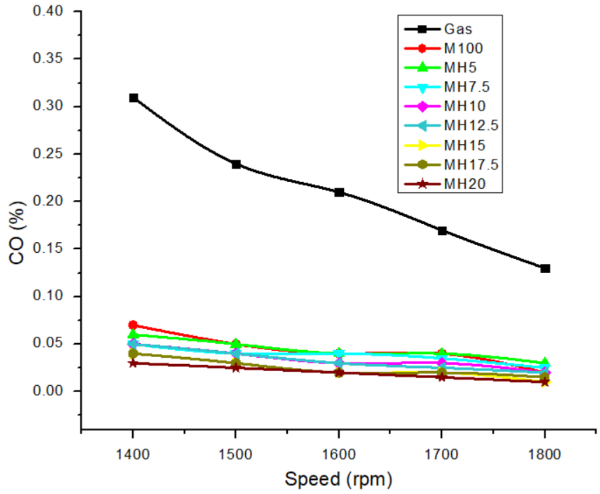


Figure 4.39 Variation of CO emission with speed for various fuels

Unlike CO_2 emissions, CO emission is found to decrease with an increase in speed, probably due to improving the favorable condition for combustion. The comparison of CO emission variation is as shown in Figure 4.39. The amount of CO emission for gasoline is found highest due to its high C-H concentration. The best combustion condition for gasoline is considered to be near stoichiometric, which at top speed is achieved, but, due to the unavailability of combustion time, unburnt HC is emitted and some CO too. However, compared to lean burning conditions, the amount of CO produced at near stoichiometric conditions is less. At low speed, because of the high heat of vaporization, M100 finds slight difficulty in combustion process, but with the increase in speed the combustion gets better. With hydrogen enrichment, the combustion quality gets improved; hence the amount of CO is further reduced, similar to HC emission. The increasing speed also increases the rate of reduction in CO emission for hydrogen enrichment, which varies from 12% per 100rpm of MH5 to 27% per 100 rpm of MH17.5. MH20 was reported to have near-zero CO emission at higher speeds, even at 1700 rpm and 1800rpmMH20 is observed to have almost 90% reduction HC per 100rpm from gasoline, while nearly 38.9% reduction per 100rpm from methanol.

CHAPTER 5

CONCLUSIONS

The primary objective of this study is to investigate the performance, combustion, and emission characteristics of a four-stroke, single-cylinder SI engine fueled with neat Methanol. Research interest focuses explicitly on the influence of the change of operating parameters such as blends, compression ratio, and ignition timing, which will reflect on the engine's overall performance, combustion, and emission characteristics.

Initially, the effect of different blend proportions of methanol and gasoline with the default operational setting gives an idea of using methanol effectively in the SI engine. Therefore, optimizing the operating parameters for the methanol/gasoline blend provides a better results interms of performance, combustion and emission characteristics.

The following conclusion are listed based on the study.

Characteristic study of different methanol/gasoline blend ratios

- The performance evaluation suggests the methanol/ gasoline blend within the flammability limit have shown good results compared to gasoline.
- M50 fuel exhibits higher thermal efficiency of 10 % more than gasoline fuel. while the power generated by the engine using M50 fuel decreases by 15% compared to the M10 blend.
- The study results results suggests, the methanol blend portion more than 50 percent is not a preferred option in the unmodified gasoline-fueled engines.
- Lower molecular mass methanol along with the excess oxygen content can lead to a more homogenous combustion. Hence exhaust gases released are lower compared to gasoline.
- The experimental investigation suggests, that increasing CR improves fuel/air proportion in the cylinder and also creates turbulence inside the cylinder which results in increased cylinder pressure and burning speed.

Characteristics study of SI engine fuelled with M50 fuel blend

- Performance and combustion results improved by 10%-15% of methanol/gasoline blends with correct ignition timing.
- Optimized ignition timing shortens the ignition delay, which results in better work transfer to the moving piston thereby minimizing the loss of chemical energy.
- Ignition timing retardation has proved productive for M50 fuelled SI engine because it exhibits excellent results.
- The exhaust emissions of NO_X,CO and HC reduced by more than 35% compared to gasoline. Increase of CO_2 suggests better burning efficiency. CO_2 percentage is much lower when compared to gasoline emissions.

Effect of change of Operating Parameters (Compression Ratio and Ignition Timing)

- Further, SI engine was operated with neat methanol by changing the compression ratio from CR11 to CR 14 at 22° BTDC; without the occurrence of knock
- The higher compression ratio (CR14) aided for good combustion and the raise of in-cylinder pressure and temperature. It accelerates the oxidation reactions of fuels, thereby speeding the start of chemical reactions
- The highest thermal efficiency of 27.8% obtained at engine speed 1500 rpm with CR14, were as the brake thermal efficiency decreases for CR13, CR12, and CR11 with values 26.1%, 22.8% and 20.01%, respectively.
- A similar trend of performance outcome is observed for BP, the power obtained with CR 14 is 21% more than the power output of CR11. The high latent heat of vaporization causes charge cooling which results in increased volumetric efficiency. CR14 results lower BSFC
- The lower carbon content methanol with good combustion characteristics has exhibited significant reduction with CO, HC and CO_2 by 40%-60% with the increase in CR. However, NO_x emission is increasing with CR and speed
- Methanol with the higher latent heat of vaporization requires slightly more time for the absorption of heat during the compression stroke, so retarding the

ignition timing (20° BTDC) for methanol operation would assist it in burning more efficiently.

- Therefore, the highest efficiency of 28.1% is observed with neat methanol 20° BTDC crank angle, whereas at least of 25.7% was seen for 26° BTDC crank angle.
- Over advancing the ignition timing has caused the early combustion, which in turn affects the compression cycle, thereby reducing the power output and the thermal efficiency.
- A small change with the BP, BSFC, and volumetric efficiency was observed. Although a little variation in CO, CO_2, and HC emission was observed, NO_x got reduced significantly due to optimal combustion timing.
- Hence the study of engine characteristics with methanol as a neat fuel in the regular SI engine has shown that higher CR and shortened Ignition delay are the ideal characteristics for good thermal efficiency.

Hydrogen enrichment to neat methanol

- The addition of hydrogen to the neat methanol tends to increase the cylinder pressure due to high flame speed and high energy content of hydrogen. MH20 has a 23.7% rise from gasoline.
- Hydrogen enrichment of 5% of hydrogen enrichment, the brake power has increased by 16% overall compared to neat methanol. Highest BP was observed with MH20 fuel, and it has increment of 12% compared to gasoline.
- The BTE values of hydrogen enriched methanol compared to M100 is as follows, for MH5, BTE increases by 0.6% compared to M100 followed with nearly 1.1 % increase for MH7.5 and MH10, the maximum raise was observed in MH12.5 of 2.5%.
- The volumetric efficiency is decreasing continuously with hydrogen enrichment due to the gaseous form of it as well as high diffusivity of it being responsible for displacing a large amount of air.
- The CO, CO_2 and HC emissions are reduced drastically with hydrogen addition due to improved combustion. However CO_2 had a increasing trend with higher speed, HC and CO emissions tends to decrease.

- NO_X increased with hydrogen addition; MH20 has seen the highest NO_X.

From the experimental investigation it can be concluded that use of neat methanol in the unaltered SI engine seems a great option. The optimization of operating parameters such as compression ratio and Ignition timing has shown a improved performance, enhanced combustion characteristics and finally, reduced emission substantially, considering the composition of methanol. Futher, the enrichment of hydrogen to the methanol-powered engine has enhanced the capability of methanol operation by delivering excellent results with respect to overall engine characteristics.

Scope of future work

- To study the engine characteristics of neat methanol operation using direct injection method. Where GDI injection is advantageous as it injects fuel at high pressure directly into the combustion chamber.
- Methanol fueled GDI engine will have the advantage of control over the injection timing and the amount of fuel delivered
- Study of using dual ignition for neat methanol fuelled engine, thereby improving the efficiency by initiating twin flame fronts, giving faster and more complete burning.
- The hybridization of engine technology for blending gaseous and liquid fuel (methanol/hydrogen) to achieve better energy utilization.
- Development of adoptive engine technology based on physical and chemical properties of fuel used.

REFERENCES

Abdu, Y. A., and Inambao, F. L. (2018). "Progress in alcohol-gasoline blends and their effects on the performance and emissions in SI engines under different operating conditions." *International Journal of Ambient Energy*, Taylor & Francis, 0(0), 1–40.

Abu-Zaid, M., Badran, O., and Yamin, J. (2004). "Effect of methanol addition on the performance of spark ignition engines." *Energy and Fuels*, 18(2), 312–315.

Agarwal, A. K., Karare, H., and Dhar, A. (2014a). "Combustion, performance, emissions and particulate characterization of a methanol-gasoline blend (gasohol) fuelled medium duty spark ignition transportation engine." *Fuel Processing Technology*, Elsevier B.V., 121(X), 16–24.

Agarwal, A. K., Karare, H., and Dhar, A. (2014b). "Combustion, performance, emissions and particulate characterization of a methanol-gasoline blend (gasohol) fuelled medium duty spark ignition transportation engine." *Fuel Processing Technology*, Elsevier B.V., 121(X), 16–24.

Al-Farayedhi, A. A., Al-Dawood, A. M., and Gandhidasan, P. (2004). "Experimental Investigation of SI Engine Performance Using Oxygenated Fuel." *Journal of Engineering for Gas Turbines and Power*, 126(1), 178.

Albayrak, B. (2012). "Use of Hydrogen-Methane Blends in Internal Combustion Engines." *Hydrogen Energy - Challenges and Perspectives*.

Alexandru, D., Ilie, D., and Dragos, T. (2017). "Evaluation of performance and emissions characteristics of methanol blend (gasohol) in a naturally aspirated spark ignition engine." *IOP Conference Series: Materials Science and Engineering*, 252(1).

Awad, O. I., Mamat, R., Ibrahim, T. K., Hammid, A. T., Yusri, I. M., Hamidi, M. A., Humada, A. M., and Yusop, A. F. (2018). "Overview of the oxygenated fuels in spark ignition engine: Environmental and performance." *Renewable and Sustainable Energy Reviews*, Elsevier Ltd, 91(March), 394–408.

Balki, M. K., Sayin, C., and Canakci, M. (2014). "The effect of different alcohol fuels on the performance, emission and combustion characteristics of a gasoline engine." *Fuel*, Elsevier Ltd, 115, 901–906.

Bechtold, R. (2007). *Use of Methanol as a Transportation Fuel. Alliance Technical Services Inc*.

Bilgin, A., and Sezer, I. (2008). "Effects of methanol addition to gasoline on the performance and fuel cost of a spark ignition engine." *Energy and Fuels*, 22(4), 2782–2788.

Brusstar, M., Stuhldreher, M., Swain, D., and Pidgeon, W. (2002). "High efficiency and low emissions from a port-injected engine with neat alcohol fuels." *SAE Technical Papers*, 2002(724).

Calam, A., Solmaz, H., Yılmaz, E., and İçingür, Y. (2019). "Investigation of effect of compression ratio on combustion and exhaust emissions in A HCCI engine." *Energy*, 168, 1208–1216.

Campos-Fernandez, J., Arnal, J. M., Gomez, J., Lacalle, N., and Dorado, M. P. (2013). "Performance tests of a diesel engine fueled with pentanol/diesel fuel blends." *Fuel*, 107, 866–872.

Canakci, M., Ozsezen, A. N., Alptekin, E., and Eyidogan, M. (2013). "Impact of alcohol-gasoline fuel blends on the exhaust emission of an SI engine." *Renewable Energy*, Elsevier Ltd, 52(x), 111–117.

Cattelan, A., and Wallace, J. (2010). "Exhaust Emission and Energy Consumption Effects from Hydrogen Supplementation of Natural Gas." *SAE Technical Paper Series*, 1(412).

Çelik, M. B., Özdalyan, B., and Alkan, F. (2011). "The use of pure methanol as fuel at high compression ratio in a single cylinder gasoline engine." *Fuel*, 90(4), 1591–1598.

Danaiah, P., Ravi Kumar, P., and Vinay Kumar, D. (2014). "The effect of ignition timing and methanol gasoline blends on the performance and emissions of the spark ignition engine." *International Journal of Ambient Energy*, 35(3), 132–138.

Dang, S., Yang, H., Gao, P., Wang, H., Li, X., Wei, W., and Sun, Y. (2019). "A review of research progress on heterogeneous catalysts for methanol synthesis from carbon dioxide hydrogenation." *Catalysis Today*, Elsevier B.V., 61–75.

Daniel, R., Tian, G., Xu, H., and Shuai, S. (2012). "Ignition timing sensitivities of oxygenated biofuels compared to gasoline in a direct-injection SI engine." *Fuel*, Elsevier Ltd, 99, 72–82.

Das, L. M. (1990). "Hydrogen engines: A view of the past and a look into the future." *International Journal of Hydrogen Energy*, 15(6), 425–443.

Du, Y., Yu, X., Wang, J., Wu, H., Dong, W., and Gu, J. (2016). "Research on combustion and emission characteristics of a lean burn gasoline engine with hydrogen direct-injection.” *International Journal of Hydrogen Energy*, Elsevier Ltd, 41(4), 3240–3248.

Elfasakhany, A. (2015). “Investigations on the effects of ethanol–methanol–gasoline blends in a spark-ignition engine: Performance and emissions analysis.” *Engineering Science and Technology, an International Journal*, Elsevier Ltd, 18(4), 713–719.

Elsemary, I. M. M., Attia, A. A. A., Elnagar, K. H., and Elaraqy, A. A. M. (2016). “Experimental investigation on performance of single cylinder spark ignition engine fueled with hydrogen-gasoline mixture.” *Applied Thermal Engineering*, Elsevier Ltd, 106, 850–854.

Eyidogan, M., Ozsezen, A. N., Canakci, M., and Turkcan, A. (2010). “Impact of alcohol-gasoline fuel blends on the performance and combustion characteristics of an SI engine.” *Fuel*, Elsevier Ltd, 89(10), 2713–2720.

Feng, H., Wei, J., and Zhang, J. (2019). “Numerical analysis of knock combustion with methanol-isooctane blends in downsized SI engine.” *Fuel*, Elsevier, 236(July 2018), 394–403.

George A. Olah, Alain Goeppert, G. K. S. P., and Beyond. (2010). “Beyond oil and gas: the methanol economy.” *literature seminar*, 8.

Gong, C., Li, D., Li, Z., and Liu, F. (2016). “Numerical study on combustion and emission in a DISI methanol engine with hydrogen addition.” *International Journal of Hydrogen Energy*, Elsevier Ltd, 41(1), 647–655.

Gong, C., Li, Z., Chen, Y., Liu, J., Liu, F., and Han, Y. (2019). “Influence of ignition timing on combustion and emissions of a spark-ignition methanol engine with added hydrogen under lean-burn conditions.” *Fuel*, Elsevier, 235(July 2018), 227–238.

Gong, C., Li, Z., Sun, J., and Liu, F. (2020). “Evaluation on combustion and lean-burn limit of a medium compression ratio hydrogen/methanol dual-injection spark-ignition engine under methanol late-injection.” *Applied Energy*, Elsevier Ltd, 277(May), 115622.

Gong, C., Li, Z., Yi, L., and Liu, F. (2019). “Comparative study on combustion and emissions between methanol port-injection engine and methanol direct-injection engine with H2-enriched port-injection under lean-burn conditions.” *Energy Conversion and Management*, Elsevier, 200(July), 112096.

Gong, C., Liu, F., Sun, J., and Wang, K. (2016). "Effect of compression ratio on performance and emissions of a stratified-charge DISI (direct injection spark ignition) methanol engine." *Energy,* Elsevier Ltd, 96(X), 166–175.

Gong, C., Liu, J., Peng, L., and Liu, F. (2017). "Numerical study of effect of injection and ignition timings on combustion and unregulated emissions of DISI methanol engine during cold start." *Renewable Energy*, Elsevier Ltd, 112(X), 457–465.

Gong, C. M., Huang, K., Jia, J. L., Su, Y., Gao, Q., and Liu, X. J. (2011). "Regulated emissions from a direct-injection spark-ignition methanol engine." *Energy*, Elsevier Ltd, 36(5), 3379–3387.

Gong, C., Peng, L., Chen, Y., Liu, J., Liu, F., and Han, Y. (2018). "Computational study of intake temperature effects on mixture formation, combustion and unregulated emissions of a DISI methanol engine during cold start." *Fuel,* Elsevier, 234(July), 1269–1277.

Gong, C., Si, X., Wang, K., Wei, F., and Liu, F. (2018). "Numerical analysis of carbon monoxide, formaldehyde and unburned methanol emissions with ozone addition from a direct-injection spark-ignition methanol engine." *Energy*, Elsevier Ltd, 144, 432–442.

Gravalos, I., Moshou, D., Gialamas, T., Xyradakis, P., Kateris, D., and Tsiropoulos, Z. (2011). "Performance and Emission Characteristics of Spark Ignition Engine Fuelled with Ethanol and Methanol Gasoline Blended Fuels." *Alternative Fuel*, 85.

He, F., Li, S., Yu, X., Du, Y., Zuo, X., Dong, W., Sun, P., and He, L. (2018). "Comparison study and synthetic evaluation of combined injection in a spark ignition engine with hydrogen-blended at lean burn condition." *Energy*, Elsevier Ltd, 157, 1053–1062.

Hu, E., Huang, Z., He, J., Jin, C., and Zheng, J. (2009). "Experimental and numerical study on laminar burning characteristics of premixed methane-hydrogen-air flames." *International Journal of Hydrogen Energy*, Elsevier Ltd, 34(11), 4876–4888.

Huang, Z., Zhang, Y., Zeng, K., Liu, B., Wang, Q., and Jiang, D. (2006). "Measurements of laminar burning velocities for natural gas-hydrogen-air mixtures." *Combustion and Flame*, 146(1–2), 302–311.

Iliev, S. (2015). "A comparison of ethanol and methanol blending with gasoline using a 1-D engine model." *Procedia Engineering*, Elsevier B.V., 100(January), 1013–1022.

Ji, C., and Wang, S. (2009). "Effect of hydrogen addition on combustion and emissions performance of a spark ignition gasoline engine at lean conditions." *International Journal of Hydrogen Energy*, Elsevier Ltd, 34(18), 7823–7834.

Ji, C., Zhang, B., and Wang, S. (2013). "Enhancing the performance of a spark-ignition methanol engine with hydrogen addition." *International Journal of Hydrogen Energy*, Elsevier Ltd, 38(18), 7490–7498.

Kak, A., Kumar, N., Singh, B., Singh, S., and Gupta, D. (2015). "Comparative Study of Emissions and Performance of Hydrogen Boosted SI Engine Powered by Gasoline Methanol Blend and Gasoline Ethanol Blend." *SAE Technical Papers*, 2015-April(April).

Khidir, D., and Atrooshi, S. (2016). "Taguchi Method for Investigating the Performance Parameters and Exergy of a Diesel Engine Using Four Types of Diesel Fuels." *ARO-The Scientific Journal of Koya University*, 4(1).

Kostka, G., and Hobbs, W. (2013). "Embedded interests and the managerial local state: The political economy of methanol fuel-switching in China." *Journal of Contemporary China*, 22(80), 204–218.

Krishnan Unni, J., Bhatia, D., Dutta, V., Das, L. M., Jilakara, S., and Subash, G. P. (2017). "Development of Hydrogen Fuelled Low NOx Engine with Exhaust Gas Recirculation and Exhaust after Treatment." *SAE International Journal of Engines*, 10(1), 46–54.

Küüt, A., Ritslaid, K., and Olt, J. (1977). "Study of potential uses for farmstead ethanol as motor fuel." *Technical Report*, 9(SPPL. ISS. 1), 125–134.

Li, J., Gong, C. M., Su, Y., Dou, H. L., and Liu, X. J. (2010). "Effect of injection and ignition timings on performance and emissions from a spark-ignition engine fueled with methanol." *Fuel*, Elsevier Ltd, 89(12), 3919–3925.

Li, Y., Bai, X. S., Tunér, M., Im, H. G., and Johansson, B. (2019). "Investigation on a high-stratified direct injection spark ignition (DISI) engine fueled with methanol under a high compression ratio." *Applied Thermal Engineering*, Elsevier, 148(August 2018), 352–362.

Li, Y., Gong, J., Deng, Y., Yuan, W., Fu, J., and Zhang, B. (2017). "Experimental comparative study on combustion, performance and emissions characteristics of methanol, ethanol and butanol in a spark ignition engine." *Applied Thermal Engineering*, 115, 53–63.

Li, Z., Gong, C., Qu, X., Liu, F., Sun, J., Wang, K., and Li, Y. (2015). "Critical firing and misfiring boundary in a spark ignition methanol engine during cold start based on single cycle fuel injection." *Energy*, Elsevier Ltd, 89, 236–243.

Liu, H., Wang, Z., Long, Y., Xiang, S., Wang, J., and Wagnon, S. W. (2015). "Methanol-gasoline Dual-fuel Spark Ignition (DFSI) combustion with dual-injection for engine particle number (PN) reduction and fuel economy improvement." *Energy*, Elsevier Ltd, 89, 1010–1017.

Liu, H., Wang, Z., and Wang, J. (2014). "Methanol-gasoline DFSI (dual-fuel spark ignition) combustion with dual-injection for engine knock suppression." *Energy*, Elsevier Ltd, 73, 686–693.

Liu, S., Cuty Clemente, E. R., Hu, T., and Wei, Y. (2007). "Study of spark ignition engine fueled with methanol/gasoline fuel blends." *Applied Thermal Engineering*, 27(11–12), 1904–1910.

Ma, F., Wang, M., Jiang, L., Deng, J., Chen, R., Naeve, N., and Zhao, S. (2010). "Performance and emission characteristics of a turbocharged spark-ignition hydrogen-enriched compressed natural gas engine under wide open throttle operating conditions." *International Journal of Hydrogen Energy*, Elsevier Ltd, 35(22), 12502–12509.

Masum, B. M., Masjuki, H. H., Kalam, M. A., Palash, S. M., and Habibullah, M. (2015a). "Effect of alcohol-gasoline blends optimization on fuel properties, performance and emissions of a SI engine." *Journal of Cleaner Production*, Elsevier Ltd, 86, 230–237.

Masum, B. M., Masjuki, H. H., Kalam, M. A., Palash, S. M., and Habibullah, M. (2015b). "Effect of alcohol-gasoline blends optimization on fuel properties, performance and emissions of a SI engine." *Journal of Cleaner Production*, Elsevier Ltd, 86, 230–237.

Masum, B. M., Masjuki, H. H., Kalam, M. A., Palash, S. M., Wakil, M. A., and Imtenan, S. (2014). "Tailoring the key fuel properties using different alcohols (C2-C6) and their evaluation in gasoline engine." *Energy Conversion and Management*, Elsevier Ltd, 88, 382–390.

Menrad, H., and Nierhauve, B. (1983). "Engine and vehicle concepts for methanol-gasoline blends." *SAE Technical Papers*.

Moffat, R. J. (1988). "Describing the Uncertainties in Experimental Results." 3–17.

Nguyen, D. K., Sileghem, L., and Verhelst, S. (2019). “Exploring the potential of reformed-exhaust gas recirculation (R-EGR) for increased efficiency of methanol fueled SI engines.” *Fuel*, Elsevier, 236(September 2018), 778–791.

Ni, P., Wang, Z., Wang, X., and Hou, L. (2014). “Regulated and unregulated emissions from a non-road small gasoline engine fueled with gasoline and methanol-gasoline blends.” *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, 36(14), 1499–1506.

Nichols, R. J. (2003). “The methanol story: A sustainable fuel for the future.” *Journal of Scientific and Industrial Research*, 62(1), 97–105.

Niu, R., Yu, X., Du, Y., Xie, H., Wu, H., and Sun, Y. (2016). “Effect of hydrogen proportion on lean burn performance of a dual fuel SI engine using hydrogen direct-injection.” *Fuel*, Elsevier Ltd, 186, 792–799.

Nuthan Prasad, B. S., and Kumar, G. N. (2019). “Influence of ignition timing on performance and emission characteristics of an SI engine fueled with equi-volume blend of methanol and gasoline.” *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, Taylor & Francis, 00(00), 1–15.

Olah, G. A. (2005). “Beyond oil and gas: The methanol economy.” *Angewandte Chemie - International Edition*, 2636–2639.

Olah, G. A., Goeppert, A., and Prakash, G. K. S. (2009). “Chemical recycling of carbon dioxide to methanol and dimethyl ether: From greenhouse gas to renewable, environmentally carbon neutral fuels and synthetic hydrocarbons.” *Journal of Organic Chemistry*, 74(2), 487–498.

Olalekan, W. S., Mansor, W., and Muhamad, W. (2017). “Performance and emission characteristics of direct-injection hydrogen enriched compressed natural gas engine employing exhaust gas recirculation at various excess air ratios .” (July).

Ozsezen, A. N., and Canakci, M. (2011). “Performance and combustion characteristics of alcohol-gasoline blends at wide-open throttle.” *Energy*, Elsevier Ltd, 36(5), 2747–2752.

Patterson, D. J., Bolt, J. A., and Cole, D. E. (1980). “Modifications for Use of Methanol or Methanol-Gasoline Blends in Automotive Vehicles.”

Pefley, R K, Browning, L H, Hornberger, M L, Likos, W E, McCormack, M C, and Pullman, B. (1977). *Characterization and Research Investigation of Methanol and*

Methyl Fuels. *Technical Report*.

Phuangwongtrakul, S., Wechsatol, W., Sethaput, T., Suktang, K., and Wongwises, S. (2016). "Experimental study on sparking ignition engine performance for optimal mixing ratio of ethanol-gasoline blended fuels." *Applied Thermal Engineering*, Elsevier Ltd, 100, 869–879.

Pulkrabek, W. W. (2013). "Livro Pulkrabek - Engineering Fundamentals of the Internal Combustion Engine." *Journal of Chemical Information and Modeling*, 53(9), 1689–1699.

Rankovic, N., Bourhis, G., Loos, M., and Dauphin, R. (2015). "Understanding octane number evolution for enabling alternative low RON refinery streams and octane boosters as transportation fuels." *Fuel*, Elsevier Ltd, 150, 41–47.

Reed, T. B., and Lerner, R. M. (1973). "Methanol: A versatile fuel for immediate use." *Science*, 182(4119), 1299–1304.

Rifal, M., and Sinaga, N. (2016). "Impact of methanol-gasoline fuel blend on the fuel consumption and exhaust emission of a SI engine." *AIP Conference Proceedings*, 1725.

Roberts, M. (2002). "Benefits and challenges of variable compression ratio (VCR)." *SAE Technical Paper*, 14(724), 03P – 227.

Shabangu, S., Woolf, D., Fisher, E. M., Angenent, L. T., and Lehmann, J. (2014). "Techno-economic assessment of biomass slow pyrolysis into different biochar and methanol concepts." *Fuel*, Elsevier Ltd, 117(PART A), 742–748.

Sheldon, D. (2017). "Methanol production - A technical history." *Johnson Matthey Technology Review*, 61(3), 172–182.

Siwale, L., Kristóf, L., Bereczky, A., Mbarawa, M., and Kolesnikov, A. (2014). "Performance, combustion and emission characteristics of n-butanol additive in methanol-gasoline blend fired in a naturally-aspirated spark ignition engine." *Fuel Processing Technology*, Elsevier B.V., 118, 318–326.

Şöhret, Y., Gürbüz, H., and Akçay, İ. H. (2019). "Energy and exergy analyses of a hydrogen fueled SI engine: Effect of ignition timing and compression ratio." *Energy*, 175, 410–422.

Su, L. W., Li, X. R., and Sun, Z. Y. (2013). "The consumption, production and transportation of methanol in china: A review." *Energy Policy*, Elsevier, 63, 130–138.

Swain, P. K., Das, L. M., and Naik, S. N. (2011). "Biomass to liquid: A prospective challenge to research and development in 21st century." *Renewable and Sustainable Energy Reviews*, Elsevier Ltd, 15(9), 4917–4933.

Topgül, T., Yücesu, H. S., Çinar, C., and Koca, A. (2006). "The effects of ethanol-unleaded gasoline blends and ignition timing on engine performance and exhaust emissions." *Renewable Energy*, 31(15), 2534–2542.

Verhelst, S., Turner, J. W., Sileghem, L., and Vancoillie, J. (2019). "Methanol as a fuel for internal combustion engines." *Progress in Energy and Combustion Science*, Elsevier Ltd, 70, 43–88.

Verhelst, S., and Wallner, T. (2009). "Hydrogen-fueled internal combustion engines." *Progress in Energy and Combustion Science*, Elsevier Ltd, 35(6), 490–527.

Wang, C., Li, Y., Xu, C., Badawy, T., Sahu, A., and Jiang, C. (2019). "Methanol as an octane booster for gasoline fuels." *Fuel*, 248(January), 76–84.

Wang, J., Huang, Z., Tang, C., and Zheng, J. (2010). "Effect of hydrogen addition on early flame growth of lean burn natural gas-air mixtures." *International Journal of Hydrogen Energy*, Elsevier Ltd, 35(13), 7246–7252.

Wang, S., Ji, C., and Zhang, B. (2010). "Effect of hydrogen addition on combustion and emissions performance of a spark-ignited ethanol engine at idle and stoichiometric conditions." *International Journal of Hydrogen Energy*, Elsevier Ltd, 35(17), 9205–9213.

Wang, S., Ji, C., Zhang, B., and Liu, X. (2014). "Lean burn performance of a hydrogen-blended gasoline engine at the wide open throttle condition." *Applied Energy*, Elsevier Ltd, 136, 43–50.

Xie, F. X., Li, X. P., Wang, X. C., Su, Y., and Hong, W. (2013). "Research on using EGR and ignition timing to control load of a spark-ignition engine fueled with methanol." *Applied Thermal Engineering*, Elsevier Ltd, 50(1), 1084–1091.

Yang, C. J., and Jackson, R. B. (2012). "China's growing methanol economy and its implications for energy and the environment." *Energy Policy*, Elsevier, 41, 878–884.

Yanju, W., Shenghua, L., Hongsong, L., Rui, Y., Jie, L., and Ying, W. (2008). "Effects of Methanol/Gasoline Blends on a Spark Ignition Engine Performance and Emissions." *Energy & Fuels*, 22(2), 1254–1259.

Yao, D., Ling, X., and Wu, F. (2016). "Experimental investigation on the emissions of a port fuel injection spark ignition engine fueled with methanol-gasoline blends."

Energy and Fuels, 30(9), 7428–7434.
Yilmaz, İ., and Taştan, M. (2018). "Investigation of hydrogen addition to methanol-gasoline blends in an SI engine." *International Journal of Hydrogen Energy*, 43(44), 20252–20261.
Yousufuddin, S., Mehdi, S. N., and Masood, M. (2008). "Performance and combustion characteristics of a hydrogen-ethanol-fuelled engine." *Energy and Fuels*, 22(5), 3355–3362.
Yu, X., Li, G., Du, Y., Guo, Z., Shang, Z., He, F., Shen, Q., Li, D., and Li, Y. (2019). "A comparative study on effects of homogeneous or stratified hydrogen on combustion and emissions of a gasoline/hydrogen SI engine." *International Journal of Hydrogen Energy*, Elsevier Ltd, 44(47), 25974–25984.
Yücesu, H. S., Topgül, T., Çinar, C., and Okur, M. (2006). "Effect of ethanol-gasoline blends on engine performance and exhaust emissions in different compression ratios." *Applied Thermal Engineering*, 26(17–18), 2272–2278.
Zhang, B., Ji, C., and Wang, S. (2016). "Performance of a hydrogen-enriched ethanol engine at unthrottled and lean conditions." *Energy Conversion and Management*, Elsevier Ltd, 114, 68–74.
Zhang, B., Ji, C., Wang, S., and Xiao, Y. (2014). "Investigation on the cold start characteristics of a hydrogen-enriched methanol engine." *International Journal of Hydrogen Energy*, Elsevier Ltd, 39(26), 14466–14471.
Zhen, X., and Wang, Y. (2013a). "Study of ignition in a high compression ratio SI (spark ignition) methanol engine using LES (large eddy simulation) with detailed chemical kinetics." *Energy*, Elsevier Ltd, 59, 549–558.
Zhen, X., and Wang, Y. (2013b). "Study of ignition in a high compression ratio SI (spark ignition) methanol engine using LES (large eddy simulation) with detailed chemical kinetics." *Energy*, Elsevier Ltd, 59, 549–558.
Zhen, X., and Wang, Y. (2015). "Numerical analysis on original emissions for a spark ignition methanol engine based on detailed chemical kinetics." *Renewable Energy*, Elsevier Ltd, 81(x), 43–51.

LIST OF PUBLICATIONS AND CONFERENCES

International Journals:

- Nuthan Prasad B. S., Kumar G. N. (2019), 'Influence of Ignition timing on Performance and Emission characteristics of a Spark-Ignition Engine fueled with Methanol blend under lean-burn', Energy Sources Part A: Recovery, Utilization, and Environmental Effects. Pp.1-15, Doi: 10.1080/15567036.2019.1670292. (SCI indexed, IF: 1)

- Nuthan Prasad B.S., Jayashish Kumar Pandey, Kumar G. N. (2019), Impact of changing Compression Ratio on Engine Characteristics of an SI engine fueled with an equi-volume blend of Methanol and Gasoline, Energy, 191(C) Elsevier. Doi: 10.1016/j.energy.2019.116605 (SCI indexed, IF: 6.082)

- Nuthan Prasad B.S., Jayashish Kumar Pandey, Kumar G. N. (2021), Effect of Hydrogen Enrichment on Performance, Combustion and Emission of a Methanol fueled SI engine, International Journal of Hydrogen Energy, Elsevier. Doi: doi.org/10.1016/j.ijhydene.2021.05.039. (SCI indexed, IF: 4.939)

Conference list:

- Nuthan Prasad B.S., Prakash K. Deep, G.N. Kumar, Combustion Analysis of N-Butanol/Fuelled in a CRDI Engine and EGR Technique, NCICEC - 2017 NITK, Surathkal, Dec, 15-17- 2017, Paper ID: 25NCICEC189.

- Venkatesh T. Lamani, Nuthan Prasad B.S., Archit. S. Ayodhya, Prakash K. Deep, Ajay Kumar Yadav, G.N. Kumar, Computational investigation of n-butanol-diesel blends and low temperature combustion in common rail diesel engine, ICONRER - 2017 SKIT, JAIPUR, FEB, 2-4- 2017, Paper ID: 202.

- Venkatesh T. Lamani, Parashuram Bedar, Nuthan Prasad B.S., Archit. S. Ayodhya, Prakash K Deep, Ajay K Yadav, Kumar G. N., Effect of n-butanol-diesel blends and injection timing on performance, emission and combustion characteristics of common rail diesel engine, ICONRER - 2017 SKIT, JAIPUR, FEB, 2-4- 2017, Paper ID: 204

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Publication Details

Papers Published	Under Review	Conference	Workshops/ Symposium	Awards and Recognitions
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