SOME STUDIES ON ENGINE PERFORMANCE AND EMISSION CHARACTERISTICS OF A SI ENGINE FUELLED WITH OXYGENATED BIO-ADDITIVE (TRIACETIN)

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CANDIDATE'S DECLARATION

I HANSHAM DEWAL, 2K18/THE/06 student of M.Tech (THERMAL ENGINEERING) hereby declare that thesis entitled "**SOME STUDIES ON ENGINE PERFORMANCE AND EMISSION CHARACTERISTICS OF A SI ENGINE FUELLED WITH OXYGENATED BIO-ADDITIVE (TRIACETIN)**" is my work which is conducted under the supervision of **Prof. Naveen Kumar** at Delhi Technological University, Bawana Road, Shahbad Daulatpur Village, Rohini, Delhi.

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ABSTRACT

Rapid exhaustion of the petroleum products has led to increase in levels of pollution up to peak levels. However, stricter emission norms and depletion of natural reserves of fossil fuels would lead the researchers to find the renewable and cleaner alternatives. Unburnt hydrocarbon and carbon monoxide are the two most hazardous emissions of the gasoline engine. These emissions are responsible for various respiratory diseases such as, asthma, lung cancer, bronchitis, emphysema and failure of reproductive organs, etc. So, in order to mitigate these emissions, many researches have been done in the past in the form of fuel modifications by introducing biofuels, varying the design of combustion chamber, and after treatments of the exhaust gas. In the present scenario, to control the emissions and fuel reserves, researchers are conducting many experiments by using the biofuels. In the global market, the demand of biofuels is increasing exponentially leading into generation of glycerol in high amount. So, to control the economy of biodiesel, a proper valorisation of the waste glycerol is needed. One of the prominent ways for the utilization of crude glycerol is acetylation of glycerol which produces triacetin. Because of extra oxygen content, and high-octane rating, the triacetin is made to be used as a fuel additive for spark ignition engine.

The present study has been carried out in two phases. The first phase covers the investigation on engine performance and emission parameters using gasoline-methanol blended fuels in four stoke spark ignition engine. By enhancing the methanol content, BTE of an engine has been increased gradually as compared to the neat gasoline operation. On the other hand, engine exhaust emissions such as: Carbon monoxide (CO), Hydrocarbon (HC), Nitrogen oxides (NOx) has been studied and found that on increasing the dosages of methanol in the fuel blends would led to decrease in the aforementioned exhaust emissions due to extra oxygen content and high latent heat of vaporization of the methanol. In addition to this, by increasing the methanol concentration up to 5% in the fuel blend, a significant reduction in the exhaust emissions is noticed. However, the efficiency of the engine is improved largely at this concentration of methanol in the fuel blends.

In the second phase of this study, the effect of addition of triacetin in the gasoline-methanol blended fuels on the engine performance and emission parameters has been carried out. A multivariate optimisation technique i.e. Response Surface Methodology (RSM) using a full factorial experimental design is employed for finding out the optimal parameters of fuel blend ratio and engine load for maximizing the engine efficiency and minimizing the exhaust emissions. Various surface plots and contour plots of engine performance and emission parameters are showed which helps to identify the effects of input factors (i.e. Dosages of methanol and triacetin, engine load) on responses (i.e. CO, HC, NOx, BTE, EGT). With the help of response surface optimizer, optimum value of input factors can be determined for maximizing the engine performance parameters and minimizing the various exhaust emissions. A confirmatory validation test is also conducted with an error nearly about 6%. With reference to gasoline-methanol blended fuels, by adding the triacetin fuel additive showed a significant improvement in engine efficiency, exhaust gas temperature by reducing the various exhaust emissions.

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ABBREVIATIONS

A/F	Air-fuel ratio
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
BDAI	Biodiesel Association of India
BP	Brake Power
BTE	Brake Thermal Efficiency
CCD	Central Composite Design
CFR	Cooperative Fuel Research
CO2	Carbon Dioxide
CO	Carbon Monoxide
EFI	Electronic Fuel Injection
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
FAME	Fatty Acid Methyl Ester
FBO	Food Business Operator
FSSAI	Food Safety and Standards Authority of India
HCHO	Formaldehyde
FY	Financial Year
G100	Gasoline 100%
G95M5	Gasoline (95%) and Methanol (5%)
G5T5	Gasoline (95%) and Triacetin (5%)
GDP	Gross Domestic Product
GIA	Gemological Institute of America
HC	Hydrocarbon

IEA	International Energy Agency
IUPAC	International Union of Pure and Applied Chemistry
INR	Indian Rupee Rate
JV	Joint Venture
LHV	Low Heating Value (kJ/kg-K)
MMT	Million Metric Tons
Mtoe	Millions of Tonnes of Oil Equivalent
NO	Nitric Oxide
NOx	Oxides of Nitrogen
ON	Octane Number
PFI	Port Fuel Injection
PSU	Public Sector Undertaking
PPM	Part Per Million
RPM	Revolutions per min
RSM	Response Surface Method
SI	Spark Ignition
TFC	Total Final Consumption
TGPE	Total Global Primary Energy
TWh	Terawatt-hour
UHC	Unburnt Hydrocarbon
VVT	Variable Valve Timing
WCO	Waste Cooking Oil

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The energy demand of any country is driven by its population and economic growth, which is increasing day by day. India having a population of 1.4 billion and one of the fastest-growing emerging economies in the world, which makes India will be very important for the future of the global energy markets. According to BP energy outlook 2019, the share of India in Total Global Primary Energy demand is set to about double to 11% by 2040 [1]. Due to the robust growth in prosperity and population size, the primary energy consumption of India will be expanded by 1.2 billion tonnes of oil equivalent or about 156% by 2040 [1]. India's energy infrastructure is primarily based on the use of coal for power generation, transport and industrial oil, and biomass for heating and cooking in rural areas. As per the BP outlook 2019, in India, it is estimated that the power generation will be increased by 207% to 4781 TWh by 2040, which is about 61% of the primary energy demand. As a result, the total CO_2 emissions will be getting double to 5Gt by 2040 which means that India’s share in global emissions increases from 7% (2020) to 14% by 2040.

1.2 CRUDE OIL SCENARIO IN INDIA

Despite these, about 77% of the consumption need in India is fulfilled by the outsourcing of crude oil. Hence due to this large consumption rate, a huge amount of import bill is imposed which has a negative impact on the Indian economy. To overcome these problems, India has to look after some alternate solutions for the twin crisis problems i.e. depletion of fossil fuels and environmental degradation. The transportation sector is the leading sector in which the maximum number of crude products is utilized and this is expected to increase exponentially. However, the energy production rate of India is quite slow, due to which the energy demand is not fulfilled completely, and hence, dependency on the other countries is increased. To fulfill the increased energy requirements, India has to increase the imports of natural gas. But, the degradation of the environment, which occurs due to the extensive use of fossil fuels is also a major challenge to tackle out. Several emissions rules and regulations for the automobile led the researchers to seek out the solutions to these huge problems.

Such problems can be solved by framing new policies and strategies in such a way that it will not only lessens the large import bill but also enhance the GDP of the nation. As per the data showed in the National Report given by the Ministry of Petroleum and Natural gas in 2017-2018, the overall production of the crude oil in India has been reduced from 36.01 MMT (in 2016-17) to 35.68 MMT (in 2017-18) i.e. 0.90% [2]. The projected production of the crude oil for the next year i.e. 2018-19 is 37.01 MMT. Moreover, the import of crude oil is also enhanced from 213.93 MMT (in 2016-17) to 220.43 MMT (in 2017-18), with this the dependency on imports is also increased from 78.4% in the FY 2014-15 to 82.9% in the FY 2017-18. The year-wise scenario of Crude Oil in India is given in table 1.1, which contains the consumption and production of crude oil products, etc.

Table 1.1: Scenario of Crude oil in India

S.No.	**Name**	**Unit**	**2013-14**	**2014-15**	**2015-16**	**2016-17**	**2017-18**	**2018-19***
1	Production of Crude oil	MMT	37.8	37.46	36.94	36.01	35.68	37.01
2	Import of Crude oil	MMT	189.24	189.43	202.85	213.93	220.43	229.54
3	Production of Petroleum Products	MMT	220.76	221.14	231.92	243.55	254.00	254.40
4	Consumption of Petroleum Products	MMT	158.41	165.52	184.67	194.60	206.17	211.03’
5	Import of petroleum products	MMT	16.70	21.30	29.46	36.29	35.46	31.87
		INR(Cr)	75896	74644	65361	71566	88374	112740
6	Export of petroleum products	MMT	67.86	63.93	60.54	65.51	66.83	62.53
		INR(Cr)	368279	288580	176780	194893	225388	288231
7	Import of LNG	MMT	12.99	14.09	16.14	18.63	19.87	21.05
		INR(Cr)	53123	57384	45038	40804	49941	69848

*: Target ‘: Estimated

From the above table 1.1, it can be observed that the production rate of various Petroleum products in the FY 2017-18 is 254.00 MMT, while in the FY 2016-17 it is 243.55 MMT. This upgradation in the rate of Production of Petroleum products shows a breakthrough improvement of about 4.29%. The target set by the Ministry of Petroleum and Natural Gas for the production of Petroleum products in the FY 2018-19 is 254.40 MMT. According to the Oil and Gas Journal, India has the oil reserves of about 5.60 billion. The consumption rate of Petroleum products in the FY 2017-18 is 206.17 MMT, while in the FY 2016-17 it is 194.60 MMT. This enhancement in the consumption rate of Petroleum products shows the dependency on petroleum products for fulfilling the energy demand nearly about 5.94% [2].

In India, crude oil production has been decreasing from the last several years. It is reduced from 37.8 MMT in FY 2013-14 to 35.68 MMT in FY 2017-18. In table 1.2 the crude oil production from different producers are given:

Table 1.2. Year-wise production of crude oil through different producers

S.No.	Producers		Unit	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19*
1	Share of PSU	Onshore	MMT	10.171	9.482	9.051	9.307	9.386	7.090
2	Share of Private/JV		MMT	9.413	9.056	8.810	8.280	8.154	6.076
Total			**MMT**	**19.584**	**18.538**	**17.861**	**17.587**	**17.540**	**13.166**
3	Share of PSU	Offshore	MMT	15.541	16.194	16.543	16.284	16.240	11.340
4	Share of Private/JV		MMT	2.663	2.729	2.546	2.137	1.905	1.437
Total			**MMT**	**18.204**	**18.923**	**19.089**	**18.421**	**18.145**	**12.777**
Grand Total			**MMT**	**37.788**	**37.461**	**36.950**	**36.008**	**35.684**	**25.943**

*Up to December 2018

Till 31.03.2018, the estimated crude oil reserves in India are about 594.49 million tonnes while the annual consumption of oil is about 15.75 Mtoe which is shown in the reports of Indian Reserves of Oil. The largest crude oil reserves in India are found in the Western Offshore (Mumbai High, Krishna-Godavari Basin) nearly 40%, while Assam holds the next adjacent position of nearly about 27% [3].

1.3 Energy scenario in India

Coal is the most important energy source in India. It contributes to nearly about 55% of the total primary energy production. From the past few years, it has been a marked increment in the contribution of crude oil and natural gas in primary energy production. As per the IEA 2020 reports, in 2017 the aggregate supply of primary energy in India was about 882.0 million tonnes of oil equivalent (Mtoe), which covers the (2/3)rd of it by domestic energy production i.e. 554 Mtoe [4]. In India, the total final consumption (TFC) is larger for the industrial sector and then succeeded by the housing sector, the ransportation sector, and the last one is the service sector which mainly includes agriculture. Figure 1.1 shows the overview of India’s energy system by fuel in 2017.

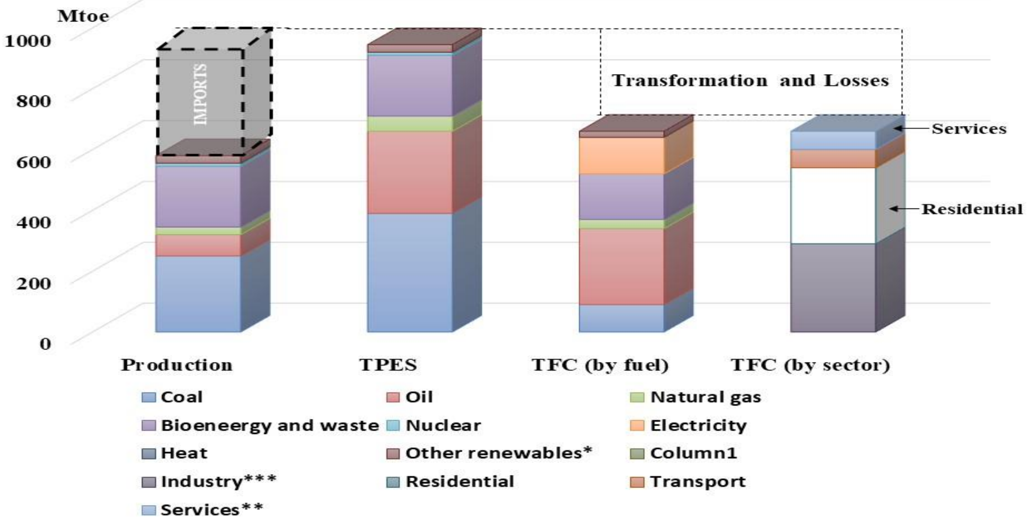


Figure 1.1. Summary of India’s energy system by fuel and sector, 2017

However, the sources for the production of energy are different, such as coal, nuclear energy, geothermal energy, oil, natural gas, biofuels, hydro energy which provides the energy security to India. Moreover, due to the increased demand for energy, its consumption is higher in India. Hence, it is essential to import various types of energy sources to fulfill the increased energy demands in India.

As per the reports published by Petroleum Planning and Analysis cell in 2013, the highest consumption of gasoline nearly about 62% was accounted for 2-wheelers [5]. This is because the majority of the middle-class income population that mainly includes schools and college students prefers to travel by 2-wheelers rather than a four-wheeler. It is very important to note down here that, two-wheeler and four-wheeler both accounts for about 95.0% of the total consumption of gasoline in India. Figure 1.2. Shows the consumption rate of gasoline in the transport sector in India.

To fulfill the energy demand by utilizing various petroleum products, harmful emissions are increasing day by day. As per the IEA report 2008, the transport sector contributed nearly 25% of the total carbon dioxide emissions in the world [6]. A considerable growth in the CO_2 emissions, from 0.3Gt in 2017 to 0.7Gt in 2040 is recorded by the transportation sector, as per the report of IEA issued in 2020. It is estimated that in the coming 20 years, the energy demand has been predicted to increase annually at the rate of nearly 6.80%. This growth is responsible for diminishing the reserves of non-renewable sources, and also depleting the environment at a large scale in the form of global warming, atmospheric pollution. With the current consumption rate, the demands of energy cannot be fulfilled by the domestic production of crude oil, because the energy reserves will remain last only for another 17.5 years. Hence, to overcome these problems researchers have to seek out the alternative solution.

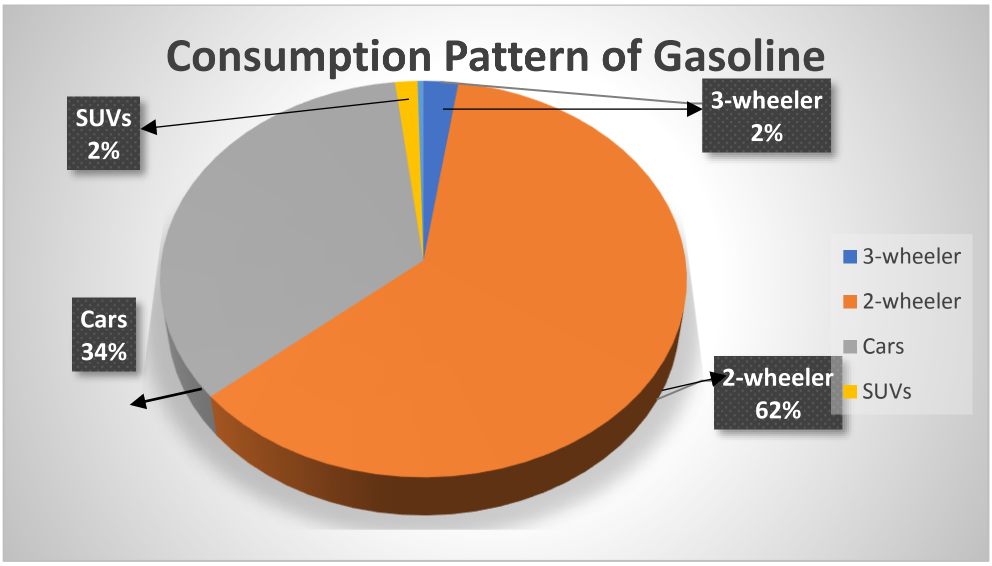


Figure 1.2. Consumption pattern of Gasoline in the Transport sector in India

1.4 Scenario of Biofuel in India

Biofuels possess the breakthrough alternative for fulfilling the growing needs of energy by utilizing the petroleum products derived from crude oil [7]. With the use of Biofuels, the dependency on foreign countries for fulfilling the fuel needs will be getting reduced. In the current situation, the demand for fossil fuels especially petrol is increasing day by day in the transportation sector. According to data presented by the Govt. of India, the necessity of the gasoline and diesel fuels is going to be widened from 26.10 MMT & 80.40 MMT in the FY 2017-18 to 31.10 MMT & 110.0 MMT by the FY 2021-22. However, if the requirement of the fuels is continuing with the same rate, then the energy security of the country will be ensured by Bio-fuels only. As these fuels, provides an eco-friendly solution and a good replacement for gasoline and diesel fuels. Currently, biofuel contributes about 3.1% of the energy which is used in transport at a global level [8]. In 2014, the biofuel production rate becomes three times i.e. 74 mega tonnes of equivalent (Mtoe) as that of in 2005 [9]. As per the report IEA 2017, the rate of biofuel production will be increased from 19 million tonnes oil equivalent (Mtoe) in 2005 to 164.0 million tonnes oil equivalent (Mtoe) by the FY 2030 [10]. The Govt. of India, also takes an initiative to reduce the problems of emissions and dependency on fossil fuel, by enhancing the consumption of biofuels. Govt. of India, has already prepared to motivate the farmers for the plantation of non-edible oils feedstock to boost the generation rate of biofuel. According to the objectives of the National Policy on Biofuels which is noticeable in 2009, proper utilization of the non-edible food stocks, supporting the research on its cultivation of wastelands for the yielding of biofuels is required and mandating the mixing ratio of 20% by 2017 [11]. Marousek et al. [12] mentioned the two finest advantages of using biofuel in the place of diesel fuels are: the absence of any aromatic hydrocarbon in the biofuel and emissions of benzopyrenes and its compounds in the exhaust are almost of low level.

In India, there are many private and public companies that are functioning in the areas of generation and distribution of Biofuels. These include Emami Biotech, Reliance Industries Ltd., Adi Biotech Pvt Ltd., Advanta Ltd., Biodiesel technocrats, Kolkata, India, etc. As per the annual progress report of the Ministry of Petroleum and Natural Gas in 2016-17, the biodiesel blend B5 is marketed by oil marketing firms in nearly about 6 states having more than 3500 retail outlets. Biodiesel Association of India (BDAI) keeps working as a coordinating agency to support the R & D and marketing of the biofuel industry.

Biodiesel which is also known as fatty acid methyl ester (FAME) is normally produced from renewable sources of energy such as vegetable oil, animal fat, nonedible foodstuffs, etc. In the production of biodiesel, the trans-esterification process of triglycerides using methanol or ethanol in the presence of an alkaline-based catalyst is involved. As the reaction proceeds, biodiesel is produced giving glycerol as a by-product. Generally, glycerol is formed with nearly about 10wt% mass balance from the reaction [13]. It is estimated that the global production of glycerol in the biodiesel market will be reached by 5.5 million tons in 2027 [14]. Glycerol is generally produced from biodiesel, thereby making it a clean and renewable burning fuel that can be used for industrial purposes. Glycerol is the main constituents in the production of resins and gums which are useful for making modern protective coatings including exterior paints, automobile enamels, etc [15]. The products of Glycerol are widely used in personal care products includes glycerine, etc. For automotive application, it is formularized as an anti-freeze agent which replaced the ethylene glycol due to a lower freezing point. It is also widely used in the motion picture industry during filming a scene that involves water to stop those parts which are drying out quickly [15]. However, the usage of glycerol is restricted due to the contaminant of fatty acid and poisonous methanol. Currently, researchers doing several types of research for the utilization of glycerol which is produced from the biodiesel production process, so that the overall cost of production can be defrayed and also encourages biodiesel production in a broader range. However, there are many ways for the effective utilization of glycerol which includes composting, biological/thermochemical conversion into valuable products, feedstuff for animals, and anaerobic digestion for producing biogas.

Acetylation process is one of the chemical transformations of glycerol that can be achieved in an effective manner. It is an acid-based catalyzed reaction generally used with an acidic solvent such as sulphuric acid. During acetylation of glycerol three types of products are produced i.e. mono-acetyl glycerides, di-acetyl glycerides, and the last one is tri-acetyl glycerides. This tri-acetyl glyceride derivative is known as triacetin which can be produced from the acetylation of glycerol in the presence of acetic acid which acts as an acid-based catalyst. Triacetin can be used for different purposes such as in the cosmetics industry, pharmaceutical industry, and many more. Triacetin can be used as a fuel additive that helps in lowering down the nitrogen oxides and harmful carbon monoxide emissions up to a greater extent.

1.5 Glycerol

It is just the simplest tri-hydric alcohol which is a colorless, odorless, sweet-tasting, and a heavy viscous liquid. It occurs naturally in the form of esters in all vegetable oil and animal fats. It is generally produced during trans-esterification of vegetable oil or animal fats, saponification, and hydrolysis reaction [16]. It is also used effectively to keep the fabrics pliable and cellophane and making the special quality of papers that may be flexible or tough. It is completely miscible with water such that during exposure in moist air it absorbs the moisture content present in the moist air. This property makes the glycerol as a valuable moistener, used in various cosmetic products. Along with the absorption of moisture, some gases are also absorbed such as hydrogen sulfide, sulfur dioxide. Moreover, it can be used for manufacturing the dynamite, and as a source of nutrients for fermentation cultures in the production of antibiotics. Table 3. depicts the physio-chemical characteristics of the Glycerol.

Table 1.3. Physio-chemical properties of Glycerol

S.No.	Property name	Unit	Property value
1	Melting Point	°C	20
2	Boiling Point	°C	290
3	Density	g/ml	1.25
4	Flash Point	°C	177

5	Storage temperature range	°C	2-8
6	Specific gravity	-	1.265
7	Viscosity	Pa-s	1.41
8	Specific heat (@25°C)	kJ/kg	2435
9	Heat of Vaporization	kJ/k-mol	82.12

Yang et al. [17] mentioned that about 1.05 ponds of crude glycerol are generated for one gallon of biodiesel production. Hence, to maintain the sustainability and viability of biodiesel industries the proper valorization of the waste glycerol is much needed. As per the GIA reports, the global market for glycerol is projected to reach 5.8 billion pounds consumption by the year 2020. As the supply of crude glycerol is increasing at a global level, some needful steps have to be taken for handling the surplus quantity of crude glycerol. In the current scenario, various researches have been taken place for the transformation of glycerol into value-added products like glycerine, glyceric acid, and ester glycerol. Among all the transformation techniques, acetylation of glycerol is one of the promising techniques that can be useful to produce fuel additive in order to enhance the various fuel properties.

1.6 Triacetin

The other name of the triacetin is glycerine triacetate and its IUPAC name are 1,2,3-tri acetoxy propane. Triacetin generally obtained from the esterification of glycerol in the presence of acetic acid, which attracts considerable attention as a fuel additive for the internal combustion engine. Currently, the demand of triacetin at a global level is nearly about 110000 tons annually. According to the global market trend research, in China, the total production of triacetin in a year is approximately 55000 tons, out of which about 385000 tons consumed domestically, and remaining is used for export purposes. Increasing the demand for triacetin that can be used as a fuel additive in the gasoline engine, in order to reduce engine knocking and tail-pipe emissions, which is expected to create a lucrative opportunity for the suppliers and manufacturers of triacetin in the next coming years. According to the study conducted by Casas et al. [18], using triacetin with the neat biodiesel up to 20 wt% can improve the quality of the fuel as per the guidelines of ASTM D6751.

It is mainly used as a gelatinizing agent and plasticizer in polymers and explosives, & can be used as an additive in tobacco, cosmetics. P.V.Rao et al. [19] enhanced engine performance by adding 10% of triacetin in biodiesel derived from coconut oil. Triacetin can be used as an anti-knocking agent to minimize the knocking phenomenon that occurs in the SI engine. Melero et al. [20] enhanced the cold flow properties of the fuel blends by adding triacetin. Table 4. shows the physicochemical properties of the triacetin.

Table 1.4. Physio-chemical properties of Triacetin

S.No.	Property name	Units	Property value
1	Melting point	°C	3
2	Boiling point	°C	258-260
3	Density	g/cm^3	1.1562
4	Flash point	°C	138
5	Auto-ignition Temperature	°C	433.33
6	Kinematic Viscosity (@40°C)	mm^2/s	7.83
7	Latent heat of Vaporisation	kJ/mol	82.0
8	High Heating Value	MJ/kg	39.9
9	Lower Heating value	MJ/kg	37.2

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In today's scenario, many researchers across the world continuing their effort to find the fuels that are much cleaner than fossil fuels for the internal combustion engine. Also, due to over-dependency on fossil fuels, the reserves of fossil fuels reduce up to great extent and degrades the environment effectively. This literature review covers all the investigation regarding the usage of methanol, blended with gasoline fuel in the gasoline engine with or without modifications. The review comprises the experimental works on finding out the performance and emission characteristics of the gasoline engine using (i) methanol-gasoline blends, (ii) the use of oxygenated additive with methanol-gasoline blends.

2.2 Literature Review

The effect of using neat methanol on the parameters of the modified 4-stroke water-cooled gasoline engine was investigated by Kajitani et al. [21]. In this experimental work, a low-pressure fuel injection system was used at the intake port. They found that

BTE was lower as compared to an unmodified gasoline engine. Also, the harmful deadly emissions such as NOx, UHC, HCHO were reduced. With the addition of water and EGR, NOx emissions are decreased while UHC is increased.

Pannone et al. [22] experimented on a single-cylinder Cooperative Fuels Research (CFR) engine fuelled with methanol. They found that the brake thermal efficiency of the engine increases with increasing the equivalence ratio. Unburnt hydrocarbon emissions (UHC) were decreasing with increasing the equivalence ratio up to 1.1, afterwards these emissions were increasing. The authors also reported that unburnt fuel emissions were minimum in a particular range of equivalence ratio i.e. 1.05-1.15. However, at higher leaner operating conditions these emissions were 80% higher than stoichiometric values.

Shenghua et al. [23] examined the effects of using gasoline-methyl alcohol blends on the performance and emissions characteristics of the 3-cylinder PFI pure petrol engine. The authors observed that with enhancing the share of methyl alcohol in the fuel blends, both engine power and torque decrease under wide-open throttle operating conditions. Moreover, on advancing the spark timing under the same operating condition both engine power and torque can be improved. Brake thermal efficiency of the engine using methanol gasoline blends was improved as compared to neat gasoline operation. However, CO and HC emissions were reduced while unburned methanol and formaldehyde emissions were enhanced as the fraction of methanol increased. The authors also concluded that, on running the engine at constant speed @2500 rpm and using the Three-way catalytic converter, the CO and HC emissions were improved when the dosage of methanol was increased as compared to the pure gasoline operation.

A study on 4-stroke gasoline engine performance parameters fuelled with methanol-gasoline blends was done by Iliev [24]. The authors found that on rising the methanol dosages in the test fuel blends and engine speed, engine brake power, engine torque, BSFC were increased as compared to the neat petrol operation. The highest value of BSFC was obtained in the M50 fuel blend. Moreover, CO and HC emissions were declined while NOx was decreased on rising the dosages of methanol in the test fuel blends.

Farkade et al. [25] investigated the performance of a two-stroke single-cylinder unmodified petrol engine fuelled with methanol-gasoline blends. They observed that using 10% methanol in gasoline fuel, effectively risen the brake thermal efficiency of the engine as compared to other test fuel blends while brake specific fuel consumption of this fuel blend was minimum.

Rohadi et al. [26] investigated the effects of using cooled EGR on the performance and emissions parameters of the four-cylinder gasoline engine using an electronic fuel injection (EFI) system fuelled with wet methanol and gasoline blends. They observed that with the use of cooled EGR and increasing the share of methanol in the fuel blends, the braking torque of the engine was increased as compared to non-EGR operation. However, BSFC of the engine fuelled with 15% wet-methanol -gasoline blend using cooled EGR @ 2500 rpm was decreased up to 12.8% as compared to non-EGR engine operation. On the other hand, brake thermal efficiency of the engine fuelled with neat gasoline using EGR was 23.5% higher than that of non-EGR engine fuelled with neat gasoline operation, while with enhancing the share of wet methanol in the fuel blends, BTE of the engine was increased for all different engine speeds. HC and CO emissions were decreased with rising the dosages of methyl alcohol in the test fuel blends while HC emission was increased and reduced the CO emissions level when the engine was equipped with cooled EGR. The CO_2 emissions were increased when the engine operation was done by the usage of cooled EGR.

The impact of using methanol in four-cylinder, four-stroke, VVT-I gasoline engine on fuel consumption and emission parameters was examined by Rifal et al. [27]. The authors reported that the fuel consumption was relatively decreased with increment in the dosage level of methanol in the test fuel blends as compared with neat gasoline operation. Moreover, the CO and HC emissions were decreased as the percentage of methanol in the fuel blend was increased.

Prayogi et al. [28] performed an experiment on four-stroke, four-cylinder gasoline engine using an electronic fuel system fuelled with acetone wet methanol and gasoline blends to find out its effects on performance and emissions characteristics of the engine. They found that increasing the content of wet methanol in the test fuel blends the brake power of the engine and exhaust gas temperature was also increased. On the other side, CO, HC emissions were decreased by increasing the concentration of wet methanol in the fuel blends.

The effect of gasoline-methanol blends on exhaust emissions of a single-cylinder four-stroke water-cooled gasoline engine was studied by Lan Li et al. [29]. They reported that, as compared to neat gasoline operation, the total hydrocarbon emission and CO emission were decreased by 11% -34.5% and 63%-84% when engine fuelled with M15 (15% methanol + 85% gasoline) fuel blend, while NOx emissions were increased by 76.99%-107.7%. On the other side, the BTE of the motorcycle engine was decreased by 16%-60% when the engine is fuelled with an M15 fuel blend.

Shayan et al. [30] experimentally investigated the impact of using methanol on performance and emission characteristics of a four-cylinder, 4-stroke VVT gasoline engine using a multipoint injection fuel system. They found that engine braking torque, engine brake power, and volumetric efficiency were increased with increasing the methanol content in the fuel blends. The brake thermal efficiency was increased while brake specific fuel consumption was decreased, with increasing the amount of methanol in the test fuel blends. The deadly engine emissions i.e. CO, HC were decreased by enhancing the share of methyl alcohol in the test fuel blends while NOx emission was increased.

Sabahi et al. [31] evaluate the effect of using methanol- unleaded gasoline blends on SI engine performance. They reported that, as compared to neat gasoline operation, brake thermal efficiency of the engine was increased by 16.78% when M10 (10% methanol + 90% unleaded gasoline) while, 22.34% when M20 fuel blend was used. Moreover, the brake specific fuel consumption of the M10 fuel blend was minimum when the engine runs at 4000 rpm.

Arapatsakos et al. [32] investigated the vehicular performance and emissions parameters of a four-stroke single-cylinder unmodified gasoline engine. They concluded that, on increasing the amount of methanol in the test fuel blend, CO and HC emissions have been reduced under idle and full load conditions. However, the brake specific fuel consumption of fuel blend was increasing with enhancing the quantity of methyl alcohol in the test fuel blend.

An analysis of the performance and emission characteristics of methanol-gasoline blended fuels (Gasohol) in naturally aspirated spark ignition (SI) engine was performed by Alexandru. et al. [33]. They observed that, on rising the dosage of methyl alcohol in the fuel blend, the power produced by the engine was decreased as the speed of engine increases. On the other hand, the CO and HC emissions have been reduced by increasing the share of methanol in the fuel blends.

Basavaraju et al. [34] evaluated the performance of the four-stroke single-cylinder gasoline engine fuelled with methanol-gasoline fuel blends. They reported that increasing the dosages of methanol in the test fuel blends would lead to decreasing the exhaust emissions i.e. CO and HC emissions, while brake thermal efficiency (BTE) of the engine was improved. Using higher percentages of methanol in the fuel blend, the brake specific fuel consumption of the engine was increased.

An investigation of the effects of ethanol-methanol gasoline blended fuel on performance and emission parameters of a single-cylinder four-stroke gasoline engine were done by Elfasakhany [35]. The author reported that amongst all the fuel blends methanol-gasoline blends showed the lowest CO and HC emissions relative to the pure gasoline operation. Moreover, methanol gasoline blends showed the highest volumetric efficiency and engine torque as compared to other test fuel blends, while ethanol-gasoline blends showed the highest brake power as compared to pure gasoline operation. On increasing the amount of methanol in a methanol-gasoline blend, CO_2 emissions were also increasing.

Yanju et al. [36] performed an experiment on three-cylinder, four-stroke PFI gasoline engine to find the effects of using methanol-gasoline fuel blends on engine performance and emissions characteristics. They found that adding methanol in the fuel blends, significantly improved the brake thermal efficiency (BTE) of the engine. With increasing the methanol concentration in the fuel blends, CO and NOx emissions were also decreased. They also concluded that, on using the M85 fuel blend, CO and NOx emissions were decreased by 25% and 80% respectively, as compared to the pure gasoline operation. Moreover, unburnt CH_3OH emissions were also increased, with the addition of methanol in the gasoline fuel blends.

Yamauchi et al. [37] studied the performance evaluation of a gasoline engine equipped with the carburettor when used with methanol mixed with gasoline with a discrete mixing ratio varied from 0% to 100%. The relationship between A/F ratio, engine performance, and ignition timing also has been studied experimentally for the mentioned setup. They reported that for higher fuel mixture large retardation of spark timing is required. For each mixed fuel condition engine, performance evaluation has been carried out to find out the best air-fuel ratio and spark timing. An equation has been derived based upon experimental data between air-fuel ration and percentage fuel mixture.

Iliev [38] developed the one-dimensional model of a four-stroke four-cylinder gasoline engine to predict the effect of various fuel types on engine performance and emissions parameters using commercial software namely AVL BOOST and the results were compared with neat gasoline operation. The authors found that on increasing the ethanol content in the ethanol-gasoline fuel blends, the engine brake power decreased for various engine speeds while BSFC were increased. On the other hand, CO, and HC emissions were decreased while NOx was decreased on enhancing the dosages of ethanol in the test fuel blends. The author also reported that on increasing the amount of methanol in the methanol-gasoline fuel blends, there was not any significant increment in the engine brake power but brake specific fuel consumption was increased at higher engine speed. Moreover, CO and HC emissions were decreased while NOx was decreased on increasing the dosages of methanol in the test fuel blends.

Sasongko et al. [39] experimentally investigated the influence of ethanol addition on the performance and emission parameters of the four-stroke single-cylinder gasoline engine. They reported that the effective brake power of the engine was decreased while specific fuel consumption was rising with enhancing the concentration of ethanol in the test fuel blends for all variations of engine speed. On the other hand, on increasing the dosage of ethanol in the fuel blends, the CO and HC emissions were reduced significantly. The authors also concluded that on average if the motorcycle was fuelled with pure ethanol, the CO emissions level has been reduced by 60% as compared to the pure gasoline operation.

Yu¨ ksel et al. [40] performed an experiment on a four-cylinder water-cooled gasoline engine fuelled with gasoline-ethanol blends for evaluating the performance and emission characteristics of the engine. They observed that, for a blended fuel i.e. (60% ethanol + 40% gasoline), the specific fuel consumption was increased and the torque of the engine and its power was reduced with enhancing the engine speed. Although, there were no significantly changes in the BTE of the engine was observed on comparing with neat gasoline operation. The harmful exhaust emissions i.e. CO, HC, NOx was also decreased for blended fuel as compared to pure gasoline.

An assessment of performance and emission parameters of single-cylinder, four-stroke unmodified gasoline engine fuelled with n-butanol-gasoline fuel blends was done by Elfasakhany et al. [41]. The authors found that at lower blend rates volumetric efficiency was lowered than that of gasoline while with increasing the fuel blend rate, volumetric efficiency was going to be higher as compared to pure gasoline operation. Similarly, with a higher blending ratio, the exhaust gas temperature showed an increasing trend, but the value of exhaust gas temperature was higher for pure gasoline as compared to blended fuels. Moreover, CO and HC emissions were decreased, with increasing the concentration of methanol and butanol in the test fuel blends. In addition, at a lowered blending rate of dual alcohols, the CO and HC emissions showed an increasing trend as compared to single alcohol and neat gasoline operation.

The effect of using fuel additive (n-butanol) in a 1-cylinder petrol engine fuelled with gasoline-methanol fuel blends was studied by Siwale et al. [42]. They observed that HC emissions were increased with the addition of n-butanol to methanol-gasoline blends when the excess ratio is increased from 1.1. However, at minimum excess air ratio, the HC emissions were deceased on adding the n-butanol in the gasoline methanol fuel blend. The authors also concluded that NOx emission was also decreased by adding 20% n-butanol in the gasoline methanol fuel blend.

The effect of using ethanol in 4-stroke, four-cylinder gasoline engine on engine performance and emissions characteristics was done by pal [43]. The author observed that CO, CO_2, NOx emissions were decreased by increasing the share of ethanol in the test fuel blend. Due to the presence of extra oxygen content in the fuel blend after the addition of ethanol, higher exhaust temperature gas was obtained.

2.3 Summary of Literature review

From the above literature review, the following conclusions can be made by considering the aspects of engine performance and emissions characteristics.

- On using the various oxygenated additives in the gasoline engine, CO and HC emissions show a decreasing nature.
- There is no particular trend is observed for brake specific fuel consumption in those studies that focus on the utilization of gasoline and methanol blends.
- There is no particular trend is observed for BTE, engine torque, engine power, and NOx emission, among the studies that utilized the oxygenated fuel additives in the gasoline engine.

2.3.1 Identification of Gaps

After analyzing the numerous researches which have been done in the above literature review, certain research gaps are identified on which further research could be done. These gaps are:

(i) There is no experimental investigation on the physical properties of fuel blends containing Triacetin as a fuel additive.
(ii) Performance of the fuel blend containing triacetin at different engine parameters, Brake thermal efficiency, exhaust gas temperature, etc. are not performed till now.
(iii) Emissions characteristics of a ternary blend containing triacetin with methanol and gasoline are uncovered until now.
(iv) A very little amount of work has been carried out on exploring the potential of glycerol as an extender fuel for CI engine.

2.3.2 Research Objectives

Following are the objectives of the present experimental work:

(i) Esterify the waste glycerol in order to produce Triacetin.

(ii) Determination of physical-chemical properties of the test fuel blends containing gasoline, methanol, and triacetin in different concentrations.

(iii) To provide an extensive multivariate analysis (RSM) of using bio-additive in gasoline methanol fuel blends on various engine performance and emission characteristics.

(iv) To determine the optimum combination of Triacetin, Methanol, and engine load in order to minimize the CO, HC, NOx, EGT, and maximize the BTE of the engine.

CHAPTER 3

SYSTEM DEVELOPMENT AND EXPERIMENTAL PROCEDURE

3.1 Introduction

Till now a lot of researches has been going on, on the production of alternative fuel which came from renewable sources of energy. Biodiesel production is one of the promising ways to fulfill the energy demands of various sectors. The preparation of biodiesel can be done using vegetable oil and some non-edible oils from plants like Jatropha, Karanja, etc. Most of the researches focused on searching out the best feedstock for the production of biodiesel, but fewer researches focused on the utilisation of the waste glycerol derived from biodiesel production as a by-product. In India, a large amount of the population is engaged in an agricultural and food industry. Due to the increased population, the demand for cooking oil is also increased. As a result, a large amount of waste cooking oil is generated. In India, the price of the waste cooking oil is cheaper than virgin vegetable oil, hence, it can be used for biodiesel production.

3.2 Capability of Waste Cooking Oil Consumption in India

Waste Cooking Oil (WCO) is used in various restaurants, hotels, household kitchens, and various types of food corners. Due to availability and low cost of WCO, it attracts keen attention in order to be used as an effective feedstock for the production of biodiesel instead of using costly crude oil and refined vegetable oils [44]. As per the information given by the president of BDAI in 2019, approximately 2500 crore liters of edible oil are consumed annually in India [45]. From the 2500 crore liters of edible oil, approximately 1670 crore liters is used by household kitchens and Food Business Operators (FBO´s) like restaurants, food corners, etc. and remaining about 834 liters is used by soaps and oleochemical manufacturing industries [45]. Hence, a large amount of WCO is generated by FBO´s in a year of about 11.45 lakh tonnes.

3.2.1 Why Choose Waste Cooking oil?

A large quantity of WCO is available all over the world. Moreover, the WCO from the restaurants and the household kitchen has some serious issues like its storage and disposable technique which is very costly. In India, most of the time the WCO is thrown away either in the river or in the sewer. However, in many kitchens, the cooking oil is used repeatedly either for frying purposes or something else. As per the FSSAI guidelines, the used cooking oil should not be used again for further cooking purposes. The officials notified the reason behind this, during the frying process several properties of the oil is changed, such as toxic total polar compound, which is directly linked to the several kinds of deadly diseases like hypertension, liver-related problems, etc [46]. Hence, a cleaner disposable technique is required in order to protect both environment and human beings also, some suitable measures need to be taken to reuse the waste vegetable oils. For this step, a large amount of money is spent on the proper treatment of the waste vegetable oils. In this way, both disposal and storage problems of the waste vegetable oil can be solved. Hence, the utilization of this alternative fuel may provide the economic benefits in order to fulfill the energy needs of several industries and automobile sectors if it is used in the diesel/gasoline engine in an effective manner.

3.2.2 Production of Biodiesel derived from Waste Cooking Oil

The most effective process for the production of biodiesel is Transesterification process [47]. In this process, triglycerides which is present in the vegetable oil can be converted into monoglycerides. So, these monoglycerides can easily react with alcohol in the presence of a suitable catalyst. After this these monoglycerides can be converted into mono-alkyl esters (biodiesel) and glycerol (by-product). Due, to transesterification of the vegetable oil a significant reduction in the viscosity property is also observed, and many other physiochemical properties of the vegetable oil are also getting enhanced. However, it can be concluded that the Transesterification process takes a lot of time and money.

The Transesterification of the waste cooking oil can be carried out by taking a 1kg of WCO in a measuring beaker, which is filtered with a cleaned cloth filter so that any suspended particles can be removed as shown in figure 3.1. The pure WCO is now placed on the heater as shown in figure 3.2 and gets heated up to 110°C so that any moisture content present in the WCO sample can be evaporated easily. After evaporation of water content, this WCO sample can be left out so that it can be cooled down at room temperature. Now, about 0.35% of the weight of the sample, NaOH (catalyst) is taken and mixed it with 200gm of methanol which is 20% wt. of the sample. For effective mixing, the magnetic stirrer can be used, as a result, the catalyst is completely mixed with the methanol. This mixture can be poured into the WCO sample slowly, and stirred well with the help of magnetic stirrer. Taking this instant as a starting time of reaction. After two hours, observe the mixture, a cloudy appearance substance is observed called glycerol which will sink to the bottom of the beaker, while methyl ester will remain at the top. When the separation between the glycerol and methyl ester has appeared clearly, stop the stirring process and allows the mixture to cool down for an overnight period in the separating funnel for phase separation as shown in figure 3.3. After this, the products of the reaction have been settled down which takes about 8 hours and producing two different phases. The biofuel is found on the top, and glycerol is found in the bottom part of the separating funnel. The biofuel can be separated from the waste glycerol by taking it into another beaker. For the water washing process, about 1 liter of water is mixed thoroughly with 0.3ml conc. H_2SO_4. This mixture is poured slowly into the biofuel and stirred well, after that this mixture is allowed to be settled down. The bottom water is found. For removing the water content, heat this mixture up to 110°C. After this, a pure form of biodiesel is obtained which is shown in figure 3.4.

Figure 3.1. Filtration Process

Figure 3.2. Heating Process

Figure 3.3. Phase separation process

Figure 3.4. Waste Cooking Oil Biodiesel

3.2.3 Production of Triacetin using Glycerol derived from WCO

The production of Triacetin can be done by using one of the most common processes i.e. Acetylation of waste glycerol. Acetylation is also known as ethanoylation; this name is given by as per guidelines of the IUPAC nomenclature. In this process, the hydrogen atom present in the hydroxyl group-containing in the glycerol is substituted by the acetyl group containing in the acetic acid. As a result, a compound containing an acetoxy functional group is formed. Figure 3.5 clearly depicts the stepwise mechanism of the conversion of Glycerol into Triacetin.

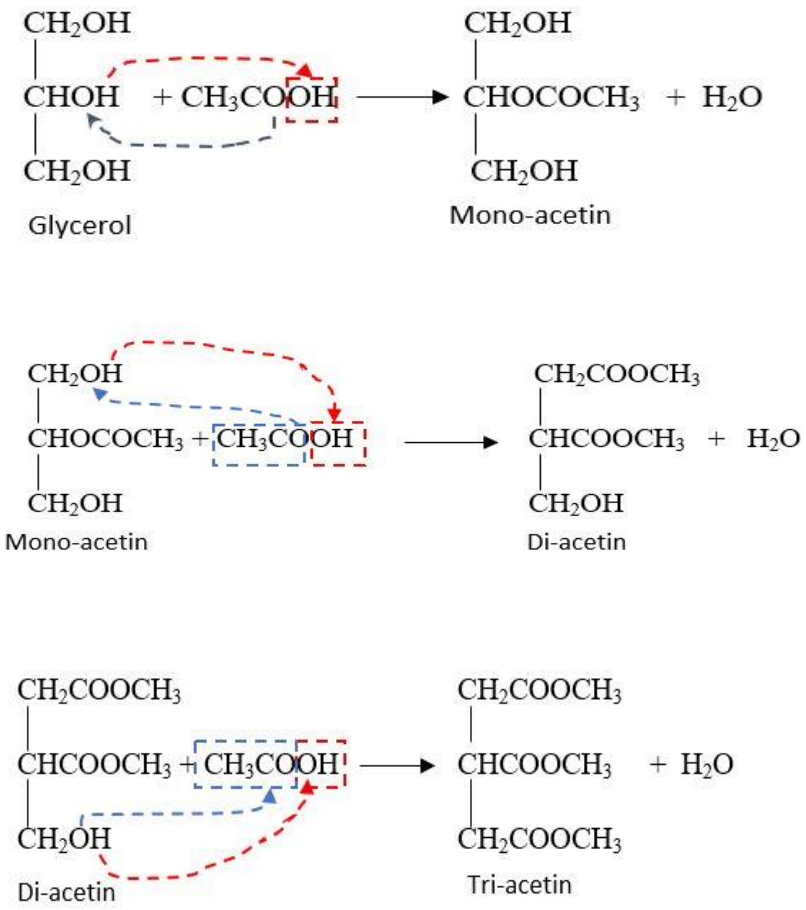


Figure 3.5. Stepwise Mechanism for the formation of Triacetin from Glycerol

In this research work, Firstly, the crude glycerol which is recovered from the WCO biodiesel is purified, then synthesis of Triacetin has been carried out in a stirred reactor. The pressure inside the reactor has to be maintained at atmospheric pressure, the speed of stirrer should be fixed nearly about 300 rpm, inside reactor temperature should be maintained within the range of 100°C-120°C. The catalyst used in this research work is from a homogenous catalyst category namely: Sulphuric acid, many literatures [48-50] proves that proves that this catalyst works fine as compared to another catalyst in the same category. The reaction was carried out in the 3-neck flask equipment with a heating mantle, a thermometer, and stirrer are attached to the flask as shown in figure

3.6. The waste glycerol which is recovered during the biodiesel production of waste cooking oil is mixed with the acetic acid (molar ratio of 1:9) in the presence of sulphuric acid (4.5wt.% of the glycerol) within the flask. The reaction time should be in the range of 0.5 hours to 7 hours. The mixture should be stirred well with the help of magnetic stirrer. After this, the parts of the products which contain sulphuric acid is to be neutralized with the usage of the same ratio of NaOH in the container. After the neutralization process, some amount of catalyst also presents in the container which can be removed by the water recirculating respiratory system. At last, the products containing glycerol, mono-acetin, di-acetin, tri-acetin, and unused part of ethanoic acid were poured in the rotatory evaporator, where all the solvents were removed from the products and hence, required product is left in the container. Figure 3.7 summarizes the preparation of Triacetin from the waste glycerol.

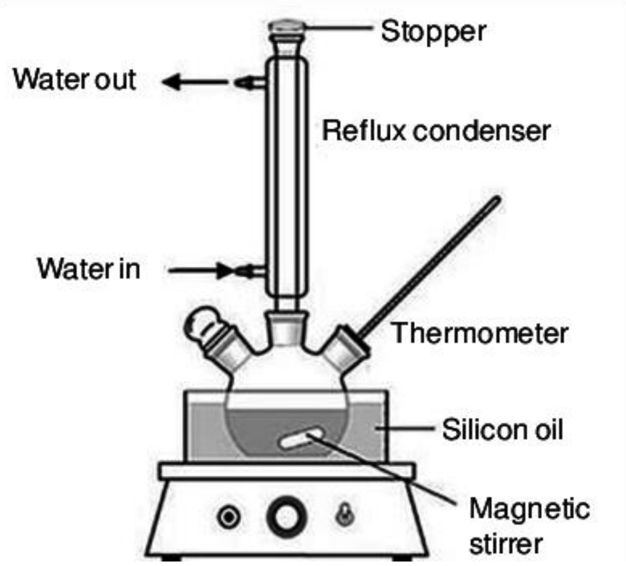


Figure 3.6. Reflux condensation setup

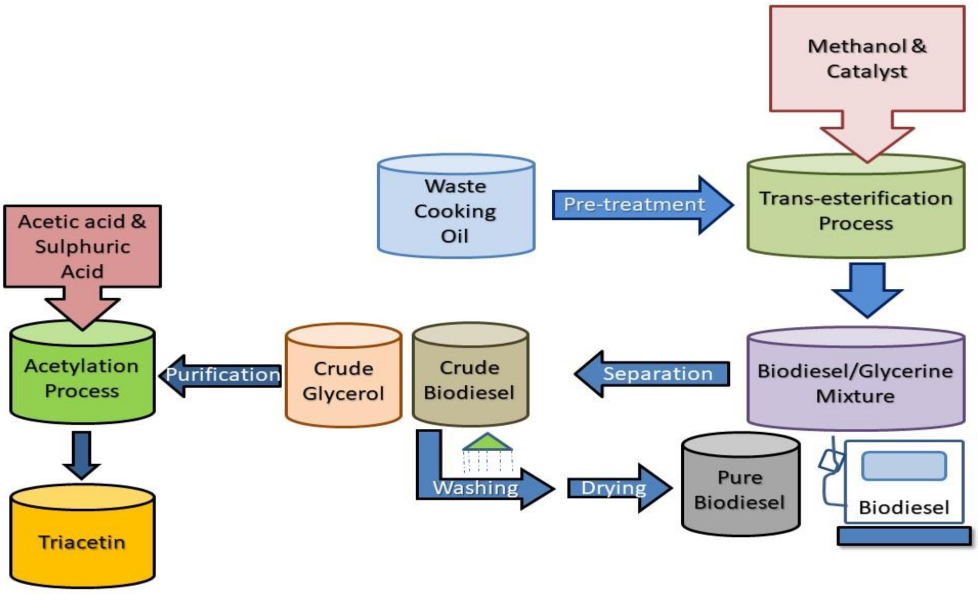


Figure 3.7. Preparation of Triacetin from waste Glycerol

3.3 Preparation of Fuel blends

The experimental work is carried out using Methanol, and its blends with Gasoline and Triacetin fuel additive. Total 10 test fuel blends containing different dosages of Methanol, Triacetin, and Gasoline are taken. The test fuel blends are represented by G95T5, G95M5, G90T10, G90M10, G90M5T5, G85T5M10, G85T10M5, G80T10M10, G80T15M5, and G80T5M10. The respective nomenclature of the test fuel blends is shown in Table 3.1. In the next section, required properties of all the fuel blends has been discussed which are measured in the CASRAE lab of Delhi Technological University.

Table 3.1. Nomenclature of the Test fuel blends with percentage content

S.NO.	**Nomenclature of the Fuel blends**	**Percentage compositions the fuels in the blends**
1	G95T5	95% Gasoline + 5% Triacetin (%v/v)
2	G95M5	95% Gasoline + 5% Methanol (%v/v)
3	G90T10	90%Gasoline + 10% Triacetin (%v/v)
4	G90M10	90%Gasoline + 10% Methanol (%v/v)
5	G90M5T5	90% Gasoline + 5% Methanol (%v/v) + 5% Triacetin (%v/v)
6	G85T5M10	85% Gasoline + 5% Triacetin (%v/v) + 10% Methanol (%v/v)
7	G85T10M5	85% Gasoline + 10% Triacetin (%v/v) + 5% Methanol (%v/v)
8	G80T10M10	80% Gasoline + 10% Triacetin (%v/v) + 10% Methanol (%v/v)
9	G80T15M5	80% Gasoline + 15% Triacetin (%v/v) + 5% Methanol (%v/v)
10	G80T5M15	80% Gasoline + 5% Triacetin (%v/v) + 15% Methanol (%v/v)

3.4 Physio-chemical properties of the Fuel blends

Different physical and chemical properties of the fuel blends are measured through different instruments. These instruments are present in the CASRAE lab of Delhi Technological University. Different fluid properties of the fuel are measured namely: density, specific gravity, calorific values, and kinematic viscosity. These fluid properties give a prior indication about the performance of the fuel in a particular engine. The primary objective of this study is to explore the different fuel properties of the aforementioned test fuel blends which may further affect the engine performance and emissions parameters.

3.4.1 Density

It is the most significant property of the fuel which should have to be determined before the utilization in an internal combustion engine. It generally signifies the heaviness of the fuel, and can be estimated by the means of the formula given below:

$$\boxed{\rho = (\text{Mass}/\ \text{volume})_{\text{of the fuel}}}$$

It is measured in kilograms per cubic meter. The thickness of the fuel droplet depicts the amount of energy contained within the droplet. The density of the fuel blend is calculated by the instrument namely: ANTON PAR, DMA-400 density meter (See Appendix 1 for more details). This property is measured at 15°C standard condition for which the instrument was calibrated. Following figure 3.8, shows the instrument which is used to measure the density of various fuel blends. The density of the different fuel blends is revealed in Table 3.2 given below.

Figure 3.8. Density Measuring Instrument

Table 3.2. Density of Distinct Fuel Blends

S.N0.	Fuel Blends	Density (g/cc)
1	G100	0.751
2	G95M5	0.773
3	G95T5	0.872
4	G90M10	0.786
5	G90T10	0.889
6	G90M5T5	0.832
7	G85M10T5	0.845
8	G85T10M5	0.951
9	G80M10T10	0.983
10	G100	0.751

3.4.2 Calorific Value:

It generally expresses the amount of heat to be released during the combustion of fuel blends which takes place under normal condition i.e. 273 K, 1.013 mbar [51]. This property is measured in MJ/kg. The measurements can be done by using Oxygen Bomb Calorimeter Parr-6100 as shown in figure 3.9 (For more details see appendix 3). The experiment can be done by taking a fuel blend sample of 1kg in the cupola, and a part of the Nichrome wire is dipped in the fuel blend. After this, the cupola is placed inside the bomb and fill the bomb with the required amount of oxygen gas. Now, put this bomb inside the bomb calorimeter chamber containing a container that is full of water. Close the lid of the instrument, and type the name and weight of the sample with the help of a coloured touch screen. Now the test run is starting, during the test run a low level of blast sound is produced which means that combustion of the fuel is completed. After some time, the calorific value of the fuel blend is shown on the touch display.

Steps involving in the calculation of Calorific value:

(i) The first step of calculating the calorific value of the fuel blend is finding out the mass of the sample using the weighing machine.

(ii) Now turn on the Bomb Calorimeter instrument. The main menu appears after the booting process.

(iii) Turn on the supply of Oxygen gas form the Oxygen gas cylinder.

(iv) Take the sample of fuel blend in the cupola and weight it. The weight of the fuel sample must be in the range of 0.80gm-1.00gm.

(v) Place the cupola containing fuel blend on the head. Attach a fuse wire in such a way that a part of the fuse wire is dipped into the weighted sample of the fuel blend.

(vi) Now put this head into the bomb cylinder, and close the lid of the bomb cylinder in such a way it does not over-tighten or loose fitted.

(vii) Now, connect the oxygen gas supply line to the head of the bomb cylinder.

(viii) Observe the touch display of the bomb calorimeter instrument, touch the icon of Oxygen fill. The supply of oxygen from the Oxygen gas cylinder to the bomb cylinder is starting. A timer is also starting that indicates after timer counting down, automatically the supply of Oxygen gas is shut off.

(ix) Now, fill the bucket with distilled water of about 2 liters.

(x) Place this bucket inside the chamber of the instrument.

(xi) With the help of a bomb lifter, place the bomb cylinder inside the bucket.

(xii) Now, connect the ignition source wires into the head of the bomb cylinder.

(xiii) Close the lid of the instrument and wait up to 15min. After 15 minutes, the calorific value of the fuel blend is shown on the touch display of the instrument.

Figure 3.9. Parr 6100 Bomb Calorimeter

In the following table 3.3, the calorific values of all the fuel blends are given.

Table 3.3. Calorific Values of the Fuel Blends

S.NO.	Fuel Blends	Calorific Value (MJ/kg)
1	G100	43.2
2	G95M5	40.3
3	G95T5	38.21
4	G90M10	37.34
5	G90T10	36.12
6	G90M5T5	39.56
7	G85M10T5	38.19
8	G85T10M5	36.51
9	G80M10T10	35.08

3.4.3 Kinematic Viscosity:

It is an atmospheric variable, defined as the ratio of the dynamic viscosity of the fuel blend to the density of the fuel blend. It can be expressed as the following mathematical formula.

$$\boxed{\nu = \frac{\mu}{\rho}}$$

In the present experimental work, this property of fuel is measured by using a measuring instrument namely: Automatic Viscosity Meter (Viscobath) as shown in figure 3.10 (for more details see appendix 2). This instrument measuring the kinematic viscosity in terms of seconds. As per the ASTM D445, the temperature should be 40°C.

Steps for measuring the Kinematic viscosity of the fuel blend

(i) Firstly, fill the tub of the viscobath with distilled water.

(ii) After switching on the machine, the temperature of the viscobath is shown in the led indicator display of the machine.

(iii) Wait for some time, for reaching the temperature of the viscobath up to 40°C.

(iv) Now, clean the Ubbelohde capillary tube as shown in figure 3.11 with some cleaning agent fluid so that any impurity within the tube is removed.

(v) After reaching the temperature 40°C, place this capillary tube with its stand inside the viscobath.

(vi) Before putting the fuel blend in the capillary tube, observe the two marks present on the surface of the tube. If these marks clearly observed, fill the fuel blend up to the top mark.

(vii) Start the stopwatch, when the fuel blend crosses the top mark of the capillary glass tube.

(viii) Now, carefully observe the marks on the glass tube, as the fuel crosses the second mark present on the glass tube, stopwatch must be stopped and note down the time taken by the fuel to travel a distance between these marks.

(ix) This measured time indicates the viscosity of the fuel blend.

(x) For calculating the kinematic viscosity use the below-given formula:

$$\boxed{v = K_c . T_f}$$

where, K is the capillary constant = 0.02702 mm^2/s^2

T_f is the time recorded by the stopwatch (in seconds).

This relationship of capillary constant and time is very useful for calculating the kinematic viscosity using capillary viscometers. If the fuel blend is more viscous then it takes a lot of time to flow through the capillary glass tube under the influence of the gravitational force. Table 3.4, shows the kinematic viscosities values of all the fuel blends.

Figure 3.10. Viscosity meter (Viscobath)

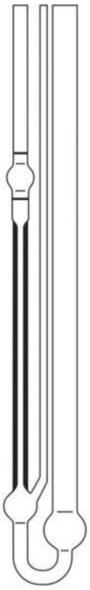


Figure 3.11. Ubbelohde capillary tube

Table 3.4. Kinematic Viscosity of the Fuel Blend

S.NO.	**Fuel Blend**	**Kinematic Viscosity (mm^2/s)**
1	G100	0.45
2	G95M5	0.49
3	G95T5	1.4
4	G90M10	0.51
5	G90T10	1.71
6	G90M5T5	1.2
7	G85M10T5	1.35
8	G85T10M5	1.62
9	G80M10T10	1.72

3.5 SELECTION OF ENGINE TESTING PARAMETERS

(i) It is very important to select engine operating parameters carefully, for the precise monitoring of the performance of an engine. Various parameters are select in this experimental work, these are Fuel consumption rate.
(ii) Speed of the engine (in RPM).
(iii) Temperature.
(iv) Brake Power produced by the engine.
(v) Emissions from the exhaust.

In order to calculate the above engine operating parameters, it is necessary to find out the values of the following terms from the test bench.

(i) Engine RPM.
(ii) The voltage produced by the alternator.
(iii) Current produced by the alternator.
(iv) Rate of fuel consumption.
(v) AVL Di-Gas analyzer.

After selecting the engine parameters, all the necessary instruments are used to find out these parameters, and these instruments are placed at a suitable point in the experimental setup. Figure 3.12, shows the test engine which is used for this experimental work, and its specification is given in table 3.5 (See appendix 4 for more details)

Figure 3.12. Test Engine setup

Table 3.5. Details of the Spark-ignition engine

Made by	**Honda**
Model	EXK 2800
Type	Four-strokes overhead-valve single-cylinder engine
Number of cylinders	1
Dimension (L*W*H)	985*471*723
Capacity of Fuel Tank	15.5 L
Cooling System	Forced Air
Spark Plug	BPR6ES (NGK)
Starting System	Recoil Starter
Ignition System	Transistor Coil Ignition system
Rated Output	2.1 kVA

3.6 INSTALLATION OF THE VARIOUS MEASURING INSTRUMENTS ON THE CONTROL PANEL

After the procurement of the essential measuring instruments, all are put on the control panel as shown in figure 3.13. A stand which is made up of iron material, and painted it with a suitable paint. The dimension of the stand is about 1030mm * 850mm, a sheet made up of bakelite material having a thickness of 3mm was mounted on the frame. Measuring instruments which are placed on the front surface of the control board is ammeter, voltmeter, RPM indicator, six channels digital temperature display. An electrical load bank as shown in figure 3.14, containing twelve bulbs each one of 500 watts, was arranged on the back surface of the control board whose ON/OFF buttons are mounted on the front surface of the control board.

Across the front surface of the panel, there is a Burette having stop cocks and 2-way valves are present. The burette is useful for the calculation of fuel flow, while two-way valves are useful for the selection of the fuel blends. Two fuel tanks are placed at the top position, on the backside of the control board, one tank is filled with Gasoline, and the other is filled with suitable fuel blend.

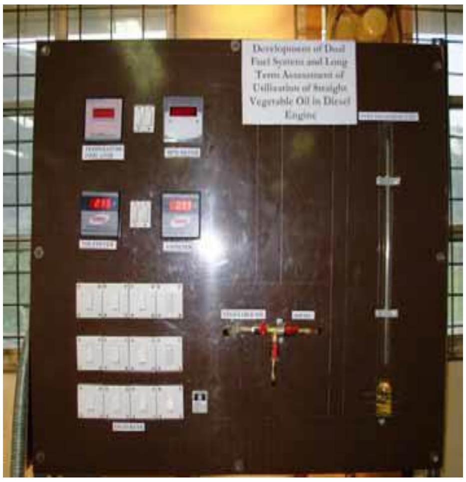


Figure 3.13. Control Panel

Figure 3.14. Load Bank

3.7 EXHAUST GAS ANALYZER

It is an instrument that is used to measure the chemical composition of the exhaust gas which is released by the engine. A typical picture of the analyzer is shown in figure 3.15. With this instrument, the efficiency of the gasoline engine can be finding out, by measuring the percentage of oxygen in the exhaust gas. In this experimental work, the blends of methanol, gasoline, and triacetin additive are analyzed based on harmful emissions of NOx, CO, and Unburnt-hydrocarbons. A brief description of the analyzer is given in the following Table 3.6, and in Appendix 5.

Table 3.6. Specification of the Exhaust Gas Analyzer

S.NO.	GAS	RANGE (BY VOLUME)	ACCURACY	RESOLUTION
1	O_2	0-25%	±0.02% vol	0.01% vol

			± 1% o.M.	
2	CO	0-15%	<10% vol: ±0.02% vol, ±3% o.M. >10% vol: ±5% o.M.	0.01/% vol
3	HC	0-30000 ppm	<2000ppm vol.: ±4ppm vol., ±3% o.M. ≥5000ppm vol.: ±5% o.M. ≥10000ppm vol.: ±10% o.M.	≤ 2000ppm vol.: 1ppm vol.
4	NOx	0-5000 ppm vol.	±5ppm vol. ±1% o.M.	1ppm vol.

Figure 3.15. AVL Exhaust Gas Analyzer

3.8 EXPERIMENTAL METHODOLOGY

Initially, the engine is allowed to run on gasoline fuel only, and about 20 min is given for the steady operation. After that, sets of fuel blends of Methanol, Triacetin with Gasoline are injected into the carburettor. As the air-fuel mixture is entered into the combustion space, the trends of various engine performance parameters and emissions parameters are studied accordingly. One thing should be noted here that firstly the engine should be run on gasoline and note down the values of the various engine performance and emissions parameters so that it can be considered as a benchmark for the whole analysis. The testing was performed by changing the blend ratio and load conditions. The load can be varied by changing the output power from the alternator side which is directly connected to the load bank. Thermocouples are used to measure the temperature at the silent point of the gasoline engine at working conditions. K type thermocouple is used to measure the temperature of the exhaust gas, placed at 200 mm from the exhaust port of the engine. The output of the thermocouple is fed to the digital temperature indicator.

With the help of gas analyzer, which is interfaced with the personal computer, records the emissions readings during each test run. These emissions readings automatically save on the computer. Following are the steps which are to be followed for the emission test:

(i) The emission test can be started by switching on the AVL Digas 444 gas analyzer. After some time, the display of the analyzer shows zero readings of the emissions.

(ii) Leak test and HC residue test should be performed by covering the probe with the help of thumb. These tests are used to be done for getting accurate readings of the various emissions.

(iii) Now, start the SI engine and make sure that initially, the engine should be run on pure gasoline and wait for some time in order to get stable conditions.

(iv) After reaching the stable condition, put the analyzer probe into the outlet of the exhaust manifold. Take the emissions readings which are shown in computer display after the emissions level reached a maximum value in 4-6 minutes.

(v) After noting the readings of emissions, remove the probe of exhaust gas analyzer, and wait for some time so that the values shown in the display should be reached to a zero value.

(vi) Repeat the above steps at different loading conditions using different fuel blends.

The engine idling was not stable with the further increment in the value of triacetin additive from 10 (%v/v). Due to the misfiring and cold start, the CO and HC emissions further increased drastically. Hence, in the present experimental work, the amount of triacetin additive in the blend is limited to 10 percent by volume.

3.9 MULTIVARIATE OPTIMISATION APPROACH-RSM

It is a set of statistical and mathematical techniques which is useful for representing and analyzing the problems in which a response variable is affected by the several independent variables [52]. The main objective of this technique is to optimize the response variable. To understand this, let us take an example, the growth of the plant is depending upon two factors i.e. the amount of sunlight which is fallen on the surface of leaves, and the amount of water which is given to the plants. Hence, in this case, the response variable y is plant growth and it is the function of the amount of water x_1, and the amount of sunlight x_2. It can be expressed as

$$y = f(x_1, x_2) + e$$

The variables x_1 and x_2 are independent variables while y is a dependent variable which is depending on both variables. In measuring the response any error is represented by the error term called statistical error which is denoted by *e*. It is generally assumed that this term is distributed normally with a mean and variance of zero values.

In this research work, the RSM optimization technique is used to optimize the fuel blend ratio and engine load, so that the engine performance can be maximized by minimizing the harmful exhaust emissions. Hence, the optimization can be obtained with the help of RSM by:

(i) Providing a crystal-clear understanding of how the input or independent variables affect the response variables.
(ii) Investigate the inter-relationships between the input variables.
(iii) Characterization of the combined effect of all the input variables that may affect the response or not.

Because of the aforementioned qualities of the Response Surface Methodology (RSM), it has been widely used, in order to determine the engine performance and emissions parameters. The process flow diagram of the RSM is shown in figure3.16

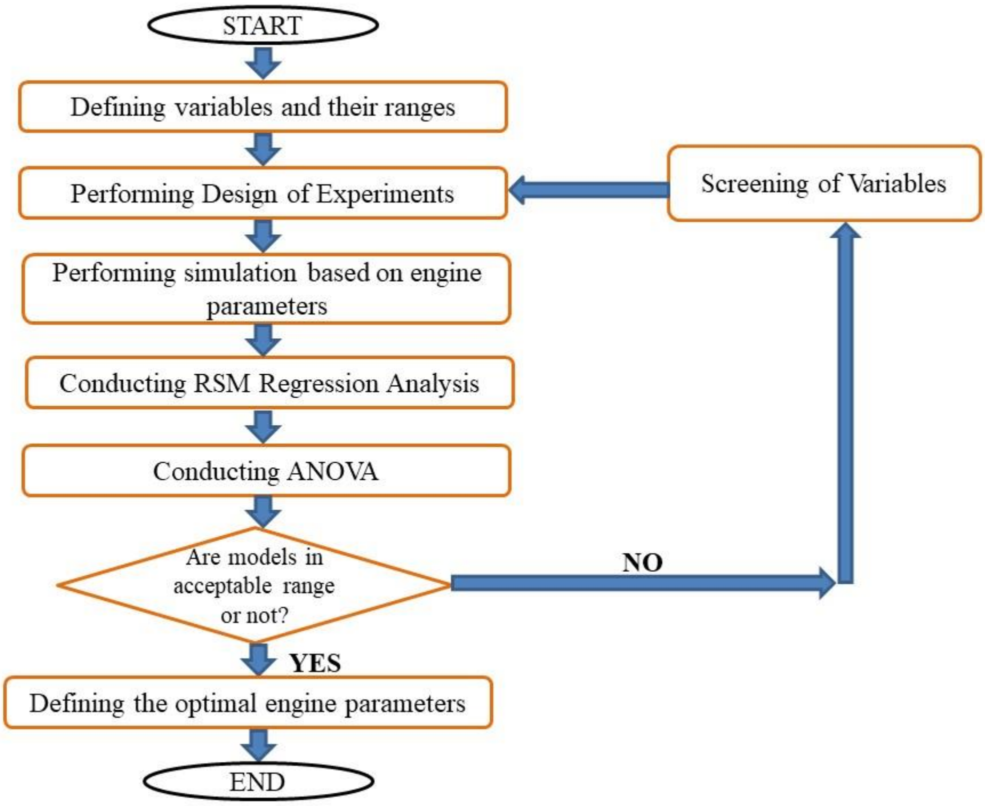


Figure 3.16. Process Flowchart of RSM

3.9.1 Response Surface Design

In this research work, a Central Composite Design is used as shown in figure 3.17, for optimizing the engine parameters. It is the most popular and widely used surface design, which combines the 2-level full factorial and 2 other kinds of points i.e.:

- **Center points**, All the factor values are at midrange (or zero) value.
- **Factorial points,** All the factors are at the corner point except midrange values.

The most important advantage of this CCD design is that it allows a space for experimentation, within the design points where the cube points are located. That's why this design is widely used by researchers. Moreover, due to the presence of corner points, the quality of the regression models is also good. Also, the total no. of experimental runs has also reduced, so that effective information can be generated in a very less time.

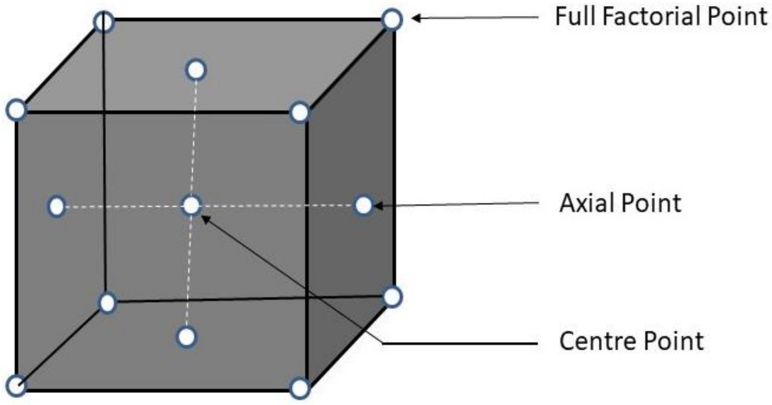


Figure 3.17. Full Factorial Central Composite Design

3.10 METHODOLOGY FOR ANALYSE THE IMPACT ON ENGINE PERFORMANCE AND EMISSIONS CHARACTERISTICS USING BIO-ADDITIVE (TRIACETIN)

The design of experiment was carried out with the help of using Minitab17 software. A three-factor, three-level Centre Composite Design based on RSM was applied. By using equation 3.1, the total number of experimental runs can be calculated.

$$\text{Total no. of runs} = 2^m + 2m + q \qquad \text{(equation 3.1)}$$

where, m is the number of independent variables = 3

2^m refers to the number of factorial points or corner points

2m refers to the number of axial points

q is the number to replicated center points

Number of experimental runs = $2^3 + 2*3 + 6 = (8 + 6) + 6 = 20$

Based on the experimental studies and exhaustive literature surveys three process variables are point out as the most significant factors namely: Methanol concentration (M) (%vol), Triacetin concentration (T) (%vol), Engine load (E) (Watts) and hence can be selected for finding out the effects on performance and emissions characteristics of the engine. In the given below Table 3.7, the coded and uncoded levels of all the 3 independent variables are given. It is common to place the variables on a common scale with the highest coded value assigns as +1 and the lowest to -1. The reason is to make sure each variable is considered on a comparable scale [53]. To avoid any biased condition 20 experimental runs were performed in randomly order form as shown in Table 3.8.

Table 3.7: Coded and Uncoded levels of the independent factors

Factors	**Coded level**		
	-1	**0**	**1**
Methanol (%vol)	0	5	10
Triacetin (%vol)	0	5	10
Engine load (watts)	300	1200	2100

To prevent any biased condition 20 experimental runs were performed in random order and analyzed with the help of the Response Surface Regression Procedure of Statistical Analysis System (RSRPSAS), according to the full factorial centre composite design as shown in Table 3.8. Correlations between independent input variables and responses are obtained by fitting them into the second-order polynomial equation which is given below:

Table 3.8. Design Matrix

Runs Order	Level of Input Variables			Responses				
	M(%vol)	T(%vol)	E(Watts)	BTE (%)	CO(%vol)	EGT (°C)	HC (ppm)	NOx (ppm)
1	(0)5	(0)5	(0)1200	26.85	0870	325	89	93.00
2	(-1)0	(1)10	(1)2100	24.31	1.250	455	110	145.00
3	(0)5	(0)5	(0)1200	26.85	0.870	325	89	90.00
4	(0)5	(0)5	(0)1200	26.85	0.870	325	89	90.00
5	(1)10	(1)10	(1)2100	23.45	1.260	450	111	170.00
6	(0)5	(0)5	(0)1200	26.85	0.870	325	89	90.00
7	(-1)0	(-1)0	(1)2100	25.65	1.265	510	112	105.00
8	(0)5	(0)5	(0)1200	26.85	0.870	325	84	90.00
9	(0)5	(0)5	(1)2100	26.40	0.884	482	95	97.00
10	(-1)0	(1)10	(-1)300	22.31	1.090	276	98	126.00
11	(0)5	(0)5	(0)1200	26.85	0.870	325	89	90.00
12	(-1)0	(0)5	(0)1200	26.82	0.874	327	93	93.00
13	(0)5	(1)10	(0)1200	24.51	1.241	315	101	135.00
14	(-1)0	(-1)0	(-1)300	23.25	1.050	275	104	95.00
15	(1)10	(-1)0	(1)2100	25.77	1.100	480	99	112.00
16	(1)10	(0)5	(0)1200	26.80	0.876	324	94	94.00
17	(0)5	(-1)0	(0)1200	25.80	0.900	300	96	93.00
18	(1)10	(1)10	(-1)300	23.01	1.150	277	103	130.00
19	(1)10	(-1)0	(-1)300	24.33	0.961	274	95	97.00
20	(0)5	(0)5	(-1)300	24.81	0.870	280	89	90.00

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ii} x^2{}_{ii} + \sum_{i=1}^{3} \sum_{j=1}^{2} \beta_{ij} x_{ij}$$

Where, y is the response i.e. BTE (%), CO (%vol), CO_2 (%vol), HC (ppm), NOx (ppm), EGT (°C), x_i, x_j are coded levels for the independent factors, β_0 is an intercept, β_i, β_{ii}, β_{ij} depicts the coefficients values for the linear, quadratic, interaction effects respectively [53]. The statistical significance of the fitted model has investigated a confidence level of 95%. Hence, with the help of these fitted models of various responses, contour plots and three-dimensional surface plots were developed, keeping any independent input factors constant at its stationary point. Many experimental runs were carried out for the sake of confirmation, in order to validate these models of various response. This validation process can be done by using various combinations of the independent input factors, which may not be a part of the original experiment.

3.11 Desirability Function for Optimization

It is one of the most used approach for optimizing the various problems of industries. This approach uses the objective function which is also known desirability function D(X) and transforms an evaluated response into a scale free value (d_j) known as desirability [54]. The ranges of the desirability function are from zero to one which means least to most desirable. The settings of input parameters or independent factors and maximum total desirability value indicates the condition of optimal parameters. An Optimum point which maximizes the desirability function, can be find out with the help of numerical optimization. In this research work, the desirability function can be used to find out the optimal engine operating values.

The desirability function has been used in the present experimental work to estimate the optimal values of the engine operating parameters i.e. independent factors (fuel blend ratio, engine load) for optimizing the engine performance and emissions characteristics.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

In this section, various results from the test performed in the previous section are discussed and displayed here. A comparative evaluation of the effect on the engine performance and emissions parameters by adding Triacetin additive in the fuel blend of Gasoline and methanol is carried out by using a multivariate optimization technique i.e. Response Surface Methodology. An optimal composition of the fuel blend ratio and engine load is determined in order to achieve the low emissions and high efficiency of the engine. Moreover, these results are compared with neat gasoline operation.

4.2 COMPOSITION OF BLENDS PREPARED

Table 4.1. Matrix of Blends

S.NO.	BLENDS	GASOLINE (%v/v)	Methanol (%v/v)	Triacetin (%v/v)
1	G95T5	95	0	5
2	G95M5	95	5	0

3	G90T10	90	0	10
4	G90M10	90	10	0
5	G90T5M5	90	5	5
6	G85T5M10	85	10	5
7	G85T10M5	85	5	10
8	G80T10M10	80	10	10
9	G80T15M5	80	5	15
10	G80T5M15	80	15	5

4.3 ANALYSIS ON ENGINE PERFORMANCE

A series of experiments were carried out on four-stroke Gasoline air-cooled engine at different engine loads from 700 kW to 2100 kW using ternary blends of Gasoline, Methanol, Triacetin having different concentration. The engine performance characteristics such as Brake Thermal Efficiency (BTE), Exhaust Gas Temperature (EGT) were evaluated and plotted against BMEP. At the final stage, these results are compared with the baseline data of Gasoline fuel.

4.4 IMPACT ON THE PERFORMANCE AND EMISSIONS PARAMETERS OF THE ENGINE BY ADDING TRIACETIN ADDITIVE IN THE FUEL BLEND USING MULTIVARIATE RESPONSE TECHNIQUE

The informative data about the performance and emissions parameters was recorded from the full factorial design. A design matrix of the data is shown in Table 3.8, is used to develop the regression equations of the various responses using Response Surface Methodology (RSM). An evaluation was made by adding Triacetin additive in the fuel blend of Gasoline and Methanol, with the help of various surface plots and contour plots. Finally, an optimal combination of the fuel blend and engine power was determined by using the desirability approach.

4.4.1 EVALUATION OF MODEL AND ANALYSIS

A second-order polynomial equation is used to develop the mathematical models for various emissions parameters, like CO, CO_2, NOx, HC, and performance parameters like Brake Thermal Efficiency (BTE), Exhaust Gas Temperature (EGT). The regression model equations of various responses are set into the following table 4.2 and obtained by applying the least square method, that fits the model into the pre-set experimental data with minimal errors. For all the responses, a full quadratic model is found to be best.

Table 4.2. Regression models for engine performance and emission characteristics

	Response	**Regression Equation**
Triacetin Additive in Gasoline-Methanol Blends	BTE (%)	21.800 +0.1368M +0.5969T+0.004978E +0.00016M*M-0.06604T*T-0.000001E*E-0.00680M*T-0.000070M*E-0.000039T*E
	EGT (°C)	279.55 -1.80M +6.64T -0.0480E+0.153M*M-0.567T*T +0.000073E*E+0.135M*T-0.000972M*E-0.002472T*E
	CO (%vol)	1.0208 -0.0165M -0.0782T+0.000020E +0.00090M*M+0.00872T*T +0.000000E*E+0.001620M*T-0.000003M*E-0.000002T*E
	CO_2(%vol)	6.941 +0.0295 +0.4035T+0.000941E -0.00189M*M-0.05189T*T -0.000000E*E+0.00406M*T-0.000023M*E-0.000056T*E
	HC (ppm)	108.80 -2.780M -4.674T-0.01127E+0.2047M*M+0.4047T*T +0.000006E*E+0.1400M*T-0.000222M*E+0.000222T*E
	NOx (ppm)	97.37 -0.906M -6.073T-0.00749E +0.1086M*M+0.9286T*T +0.000005E*E+0.0000M*T+0.000167M*E+0.000389T*E

For validating the models which are enlisted in the above table 4.2 a tool is used namely: ANOVA. It is a statistical procedure that is used to test the degree up to which the two or more groups vary in an experiment. In other words, it is often helpful to test whether or not multiple regression fit is statistically important for the complete quadratic model. The statistical significance values of the independent factors and their interactions with the different reactions with the help of F-statistic are also estimated. The peak values of the F-statistics for a specific factor give greater significance to the influence of the factor on the response [55]. The ANOVA results for the various responses i.e. engine performance and emissions characteristics are given in table 4.3- table 4.7. All the models present in table 4.3- table 4.7 are statistically significant at a 95% confidence level. From the table of the responses, it is clearly observed that almost all the factors have a significant effect on the responses. Those factors which have a p-value less than 0.05, denotes that the factor effects are significant at 95% confidence level. The criteria used to test the model are shown in the table, R^2 which is also known as the coefficient of determination, which provides an indicator of fitness [56]. The goodness of fit shows us how well the experimental results and the expected values of the built models match each other effectively. The range of R^2 is 0-1, where 0 indicates the poor fit, and 1 indicates a good fit. Hence, all the models which are enlisted in the table have an R^2 value greater than 0.90, which means that the regression fits the data very well. The significance of the adjusted R^2 is that it would be penalized for the addition of new variables that do not improve the quality of the existing model [57]. This factor can also be used to judge the goodness of the model in the case of multiple variables in a linear regression equation. Larger values of the adjusted R^2 signifies the accuracy of the model. In Table, all the models have adjusted R^2 values greater than 0.9 except CO (%vol). The predicted R^2 value of the model indicates the predictive quality of the model, how well the model predicts a set of new data [58]. In other words, if any data point from the data matrix is removed, then how much the model is capable to find out the correct value of that data point? The difference between the values of Predicted R^2 and Adjusted R^2 should be less than 0.2 [59]. This indicates that the models are subjected to be in good agreement. Table 4.8 shows the predicated R^2 values of all the models. In the next section, one by one all the engine performance and emissions characteristics are discussed.

Table 4.3. ANOVA analysis for BTE (%)

SOURCE	BTE (%)		
	SS	F-value	P-value
Model	45.0100	430.79	0.0000
M-Methanol	0.1040	9.96	0.012
T-Triacetin	5.19484	497.54	0.000
E-Engine Load	6.1937	592.80	0.000
M*T	0.2312	22.13	0.001
M*E	0.7938	75.97	0.000
T*E	0.2450	23.45	0.001
M^2	0.0000	0.00	0.951
T^2	7.3173	700.34	0.000
E^2	3.722	370.61	0.00
Error	0.000487	-	-
Total	45.1041	-	-

Table 4.4. ANOVA analysis for EGT (°C)

SOURCE	EGT (°C)		
	SS	F-value	P-value
Model	116104	174.24	0.000
M-Methanol	144	2.14	0.175
T-Triacetin	436	6.54	0.031
E-Engine Load	99003	1485.76	0.000

M*T	91	1.37	0.272
M*E	153	2.30	0.164
T*E	990	14.86	0.004
M^2	39	0.59	0.461
T^2	539	8.08	0.019
E^2	9450	141.81	0.000
Error	0.15875	-	-
Total	116704.15	-	-

Table 4.5. ANOVA analysis for CO (%vol)

SOURCE	CO (%vol)		
	SS	F-value	P-value
Model	0.440119	11.44	0.001
M-Methanol	0.003312	0.86	0.378
T-Triacetin	0.051123	13.28	0.005
E-Engine Load	0.040069	10.41	0.010
M*T	0.013122	3.41	0.098
M*E	0.001984	0.52	0.491
T*E	0.000882	0.23	0.644
M^2	0.001358	0.35	0.567
T^2	0.127553	33.14	0.000
E^2	0.001955	0.51	0.494
Error	0.005684	-	-
Total	0.474759	-	-

Table 4.6. ANOVA analysis for HC (ppm)

SOURCE	HC (ppm)		
	SS	F-value	P-value
Model	1585.05	35.89	0.000
M-Methanol	22.50	5.09	0.050
T-Triacetin	28.90	6.54	0.031
E-Engine Load	122.50	27.74	0.001
M*T	19.00	22.19	0.001
M*E	8.00	1.81	0.211
T*E	8.00	1.81	0.211
M^2	70.30	15.92	0.003
T^2	274.77	62.22	0.000
E^2	70.30	15.92	0.003
Error	12.50	-	-
Total	1624.80	-	-

Table 4.7. ANOVA analysis for NOx (ppm)

SOURCE	NOx (ppm)		
	SS	F-value	P-value
Model	7714.97	107.18	0.000
M-Methanol	36.10	5.02	0.052
T-Triacetin	3385.60	470.36	0.000
E-Engine Load	490.00	68.08	0.000
M*T	0.00	0.00	1.000
M*E	4.50	0.63	0.449
T*E	24.50	3.40	0.098
M^2	19.80	2.75	0.132
T^2	1446.70	200.99	0.000

E^2	47.70	6.63	0.030
Error	0.000025	-	-
Total	7779.75	-	-

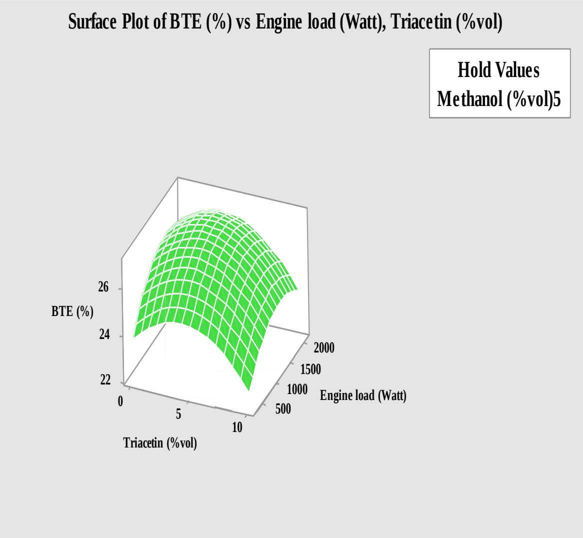
Table 4.8. Evaluation of Model

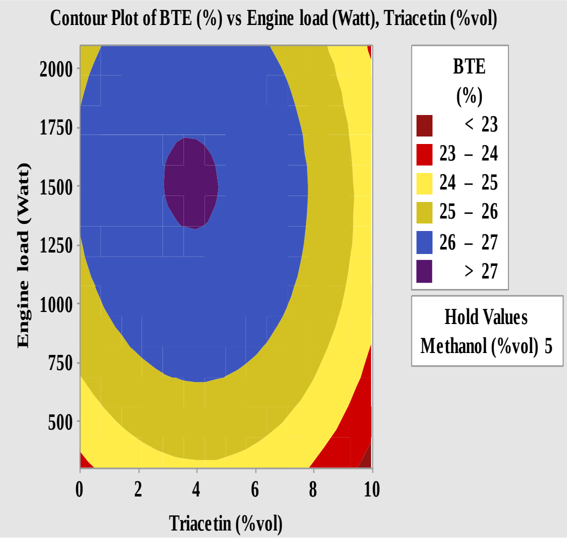
Model	BTE (%)	EGT (°C)	CO (%vol)	HC (ppm)	NOx (ppm)
R^2 (%)	99.79	99.49	92.70	97.55	99.17
Adjusted R^2 (%)	99.56	98.92	84.60	94.84	98.24
Predicted R^2 (%)	96.63	94.59	34.51	85.99	92.17

4.4.1.1 Brake Thermal Efficiency

The collective impact of the engine load, concentration of Methanol, and Triacetin on the Brake Thermal Efficiency (BTE) of the engine are depicted in the figure. 4.1. It can be noticed that, on holding the concentration of Methanol i.e. 5 (%vol) in the fuel blend, the BTE value of the engine is increased with enhancing the dosages of triacetin in the fuel blend up to 5 (%vol) while, BTE is decreasing with further increasing the concentration of Triacetin. This can be attributed due to the cumulative impact of both smaller calorific value and larger viscosity value arising with increasing the dosage of triacetin in the fuel blend.

On the other hand, by fixing the dosage level of triacetin 5 (%vol), and rising the concentration of methanol shows a negative impact on efficiency. The reason behind the decreasing trend of BTE is due to the poor burning of the test fuel blend within the engine cylinder. In addition to this, the engine efficiency increases and attains a maximum value up to 1200Watt engine load, whereas it starts decreasing with further increment in the engine load. It is due to, the presence of a low air-fuel ratio at full load, which results in decreasing the value of BTE. A similar effect has been observed in the majority of previous literature survey available on different oxygen-rich fuel additives used in spark-ignition engines (60-62)





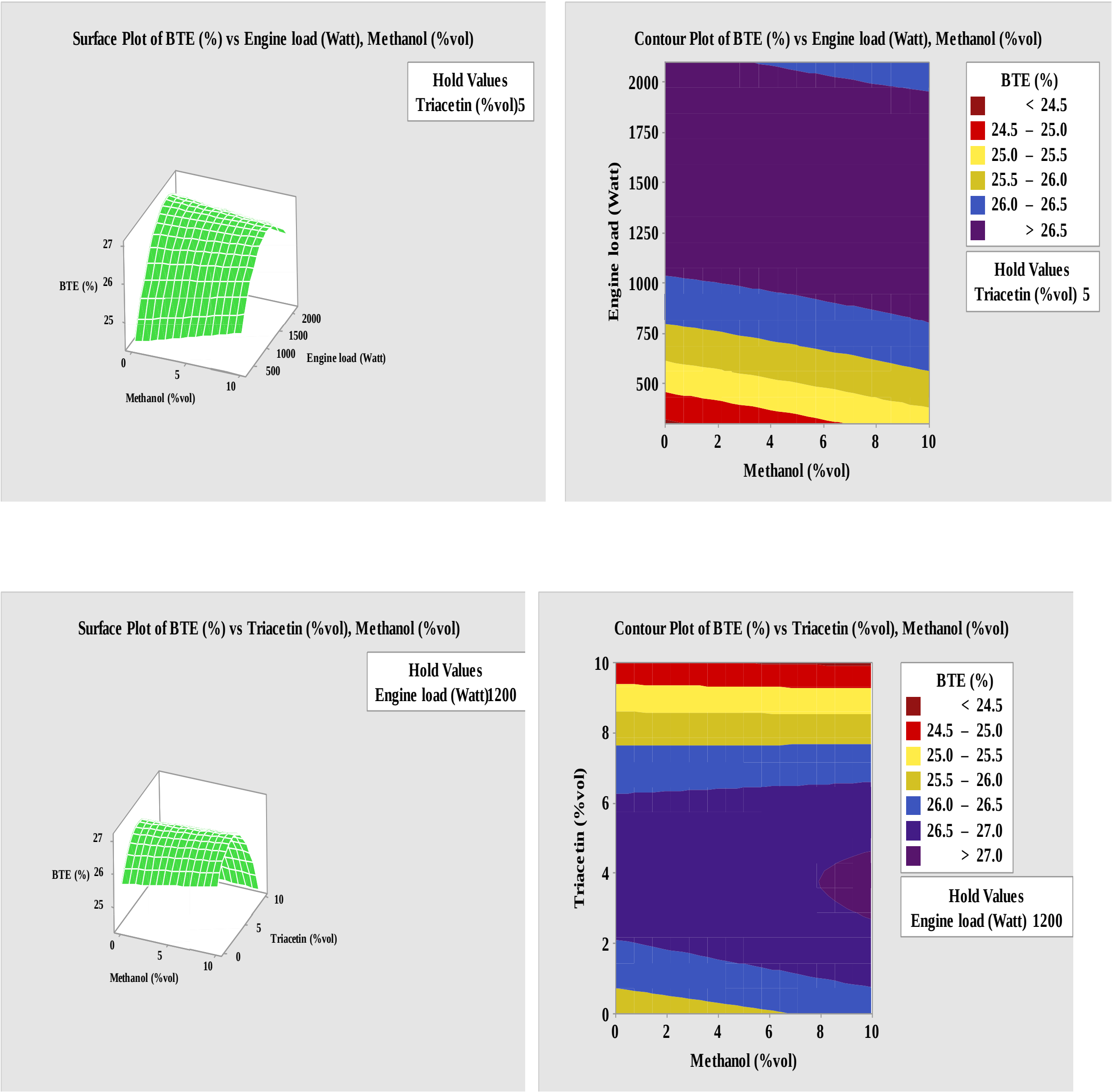
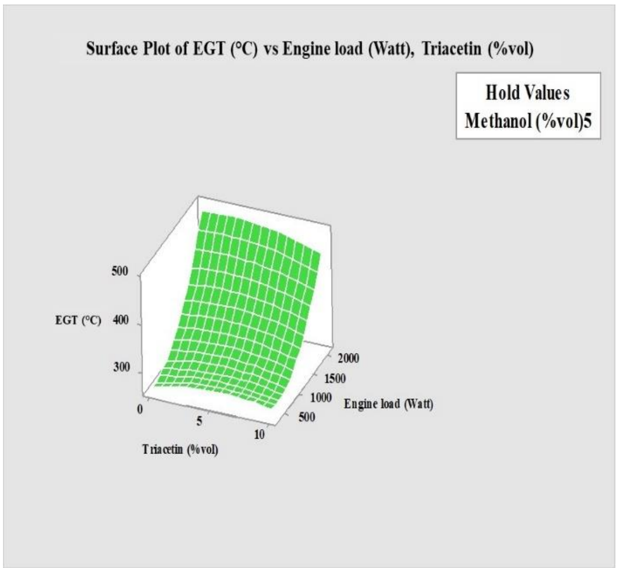


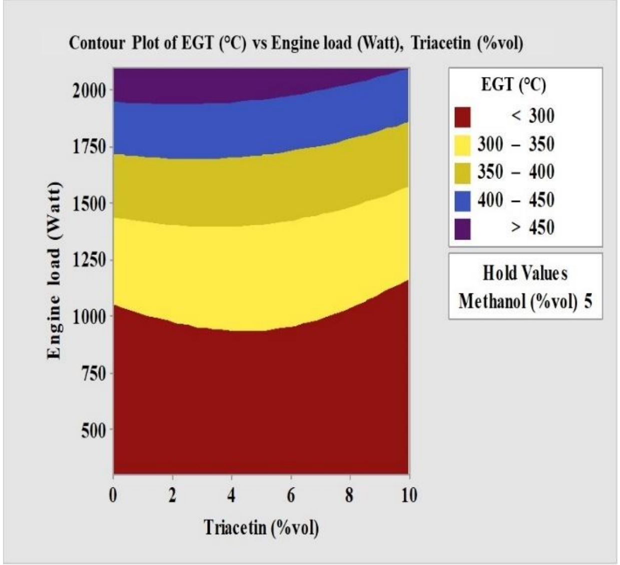
Figure 4.1. Interactive effect of Methanol, Triacetin and engine load on BTE

4.4.1.2 Exhaust Gas Temperature

The combined effects of the Triacetin, Methanol, and Engine load on the temperature of the exhaust gas released by the engine are shown in figure 4.2. It can be observed that holding the concentration of methanol in the blend i.e. 5 (%vol), and increasing the amount of triacetin up to 5 (%vol) in the blend, the EGT shows an increasing trend and reaches a higher value. This can be attributed due to the existence of extra 0xygen, complete combustion of the fuel blend inside the cylinder can occur. However, with further increasing the share of triacetin, the EGT starts decreasing due to the combined effect of high latent heat of vaporization and smaller calorific value of triacetin, which tends to decrease the inside temperature of the engine cylinder [63].

Moreover, on increasing the engine load up to 1200 Watt, the EGT curve tends to increase, it is due to the complete burning of the fuel blend inside the cylinder, which leads to rise the engine cylinder temperature. But, with further increasing the engine load, the EGT curve tends to increase drastically. It is because, at higher loads, a rich air-fuel mixture is present inside the cylinder, on combustion of the fuel blends, a larger temperature value has been reached.





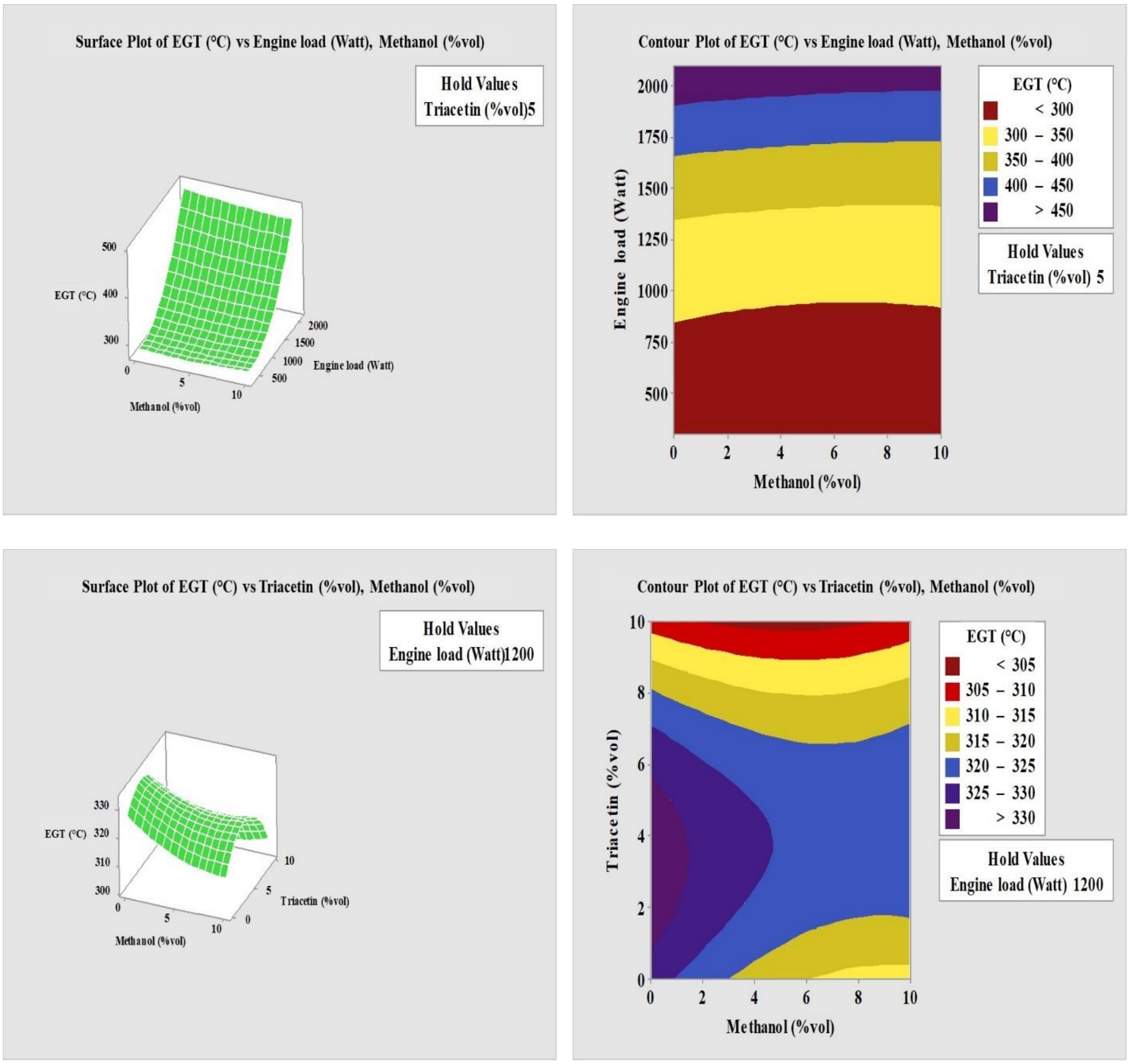
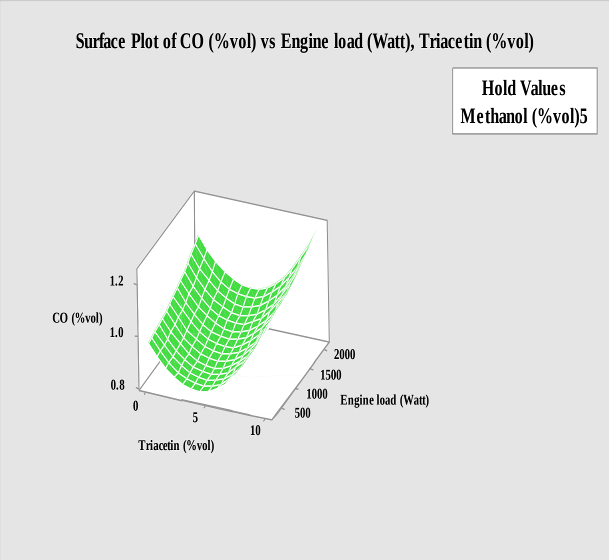


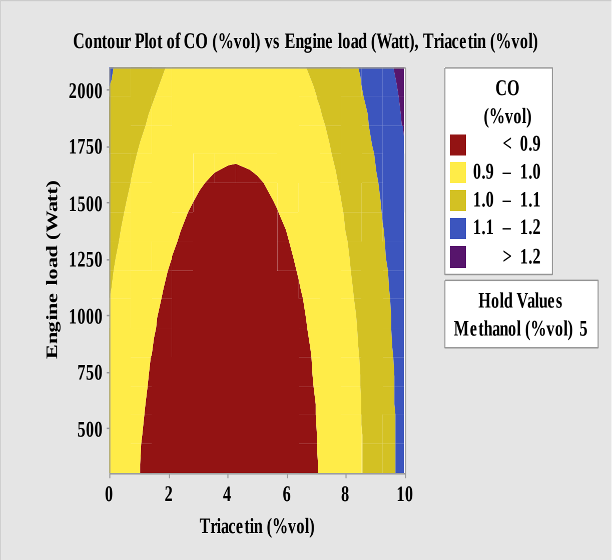
Figure 4.2. Interactive effects of Methanol, Triacetin and Engine load on EGT

4.4.1.3 CO emissions

The collective effects of the engine load, concentration of triacetin/methanol in the fuel blends on the CO emissions are illustrated in figure 4.3. It can be observed that holding a fixed amount of methanol in the fuel blends i.e. 5 (%vol), and as increasing the dosage value of triacetin up to 5 (%vol) the CO emissions tend to decrease while with further increment in the share of triacetin these emissions tend to increase. This can be attributed, due to the availability of a sufficient amount of oxygen which improves the oxidation of carbon atoms and hence reduces the chances for the formation of CO. Moreover, due to the high viscosity of Triacetin, the oxidation rate of carbon atoms has been reduced which increases the CO emissions.

On the other side, the influence of engine load on CO emissions is analyzed by restricting the dosage of Methanol and Triacetin in the fuel blends. The emissions are increasing with increasing the engine load and reaches the highest level at full load. This is because, at lower loads, the mixing of the air-fuel mixture is not appropriate which tends to raise the carbon monoxide emissions. Moreover, at higher loads, due to the supply of rich air-fuel mixture, the oxidation of CO to CO_2 is reduced which tends to increase the carbon monoxide emissions.





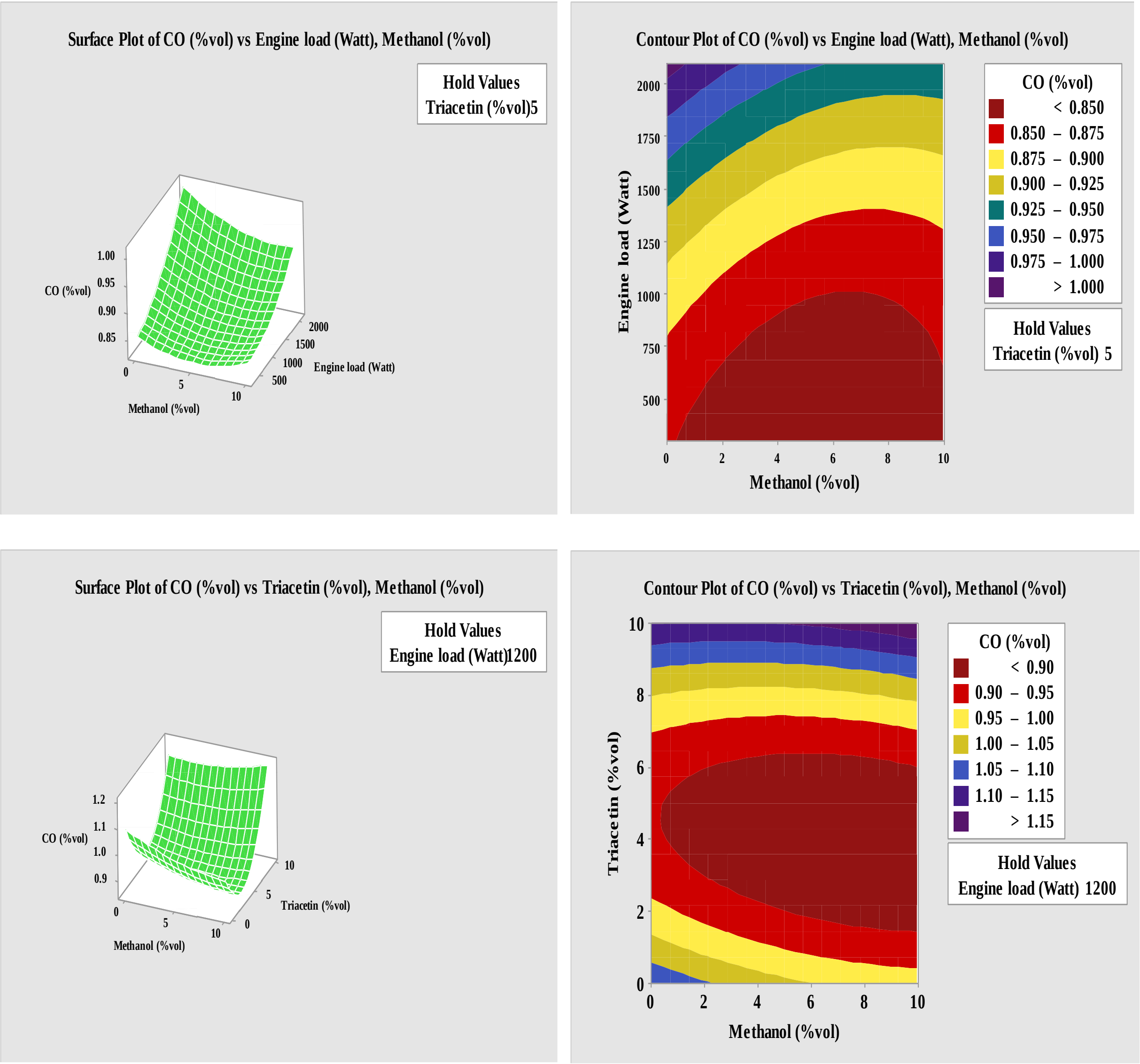
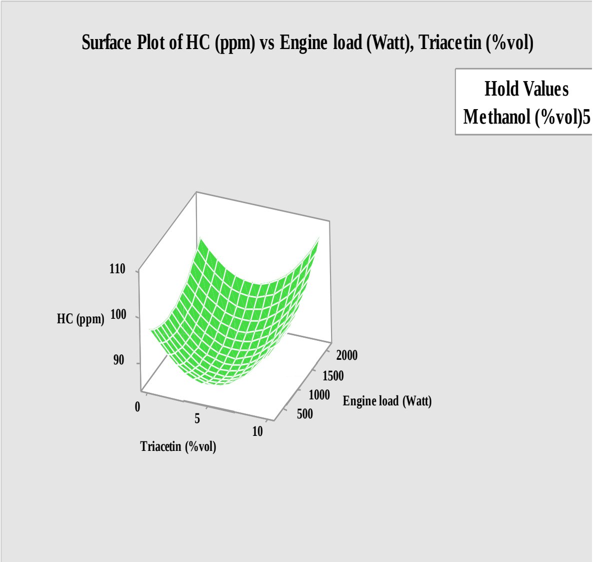


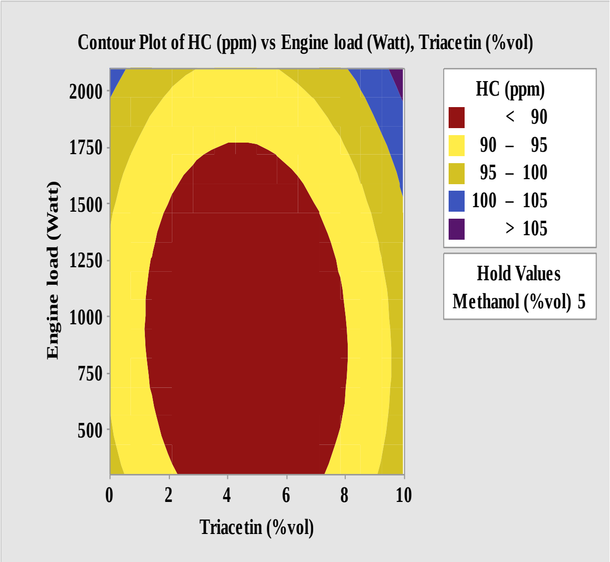
Figure 4.3. Interactive effects of Methanol, Triacetin and Engine load on CO emissions

4.4.1.4 HC emissions

The cumulative impacts of the engine load and share of methanol and triacetin in the fuel blends on the HC emissions portrays in figure 4.4. From the figure, it can be noted that by fixing the methanol concentration at a constant engine load and increasing the triacetin amount up to 5 (%vol) in the fuel blend results in decreasing the HC emissions. The reason behind this is due to the availability of extra oxygen, complete combustion takes place inside the cylinder. On further increasing the Triacetin share in the fuel blend, HC emissions tend to increase. This is due to the partial combustion of the fuel blend due to the larger value of the viscosity of the triacetin.

On the other hand, fixing the concentration of Triacetin i.e. 5 (%vol) in the fuel blend and increasing the share of methanol up to 5 (%vol) leads to decreasing the HC emissions. This is due to the higher burning velocity of the methanol, which enhances the burning rate of fuel blends [29]. But, with further increasing the amount of Methanol, HC emissions tend to increase. This can be attributed to the reduction in-cylinder temperature due to the greater value of latent heat of vaporization of methanol as compared to gasoline. This lower temperature can cause the chance of misfire or partial burn in the region near the cylinder wall [29].





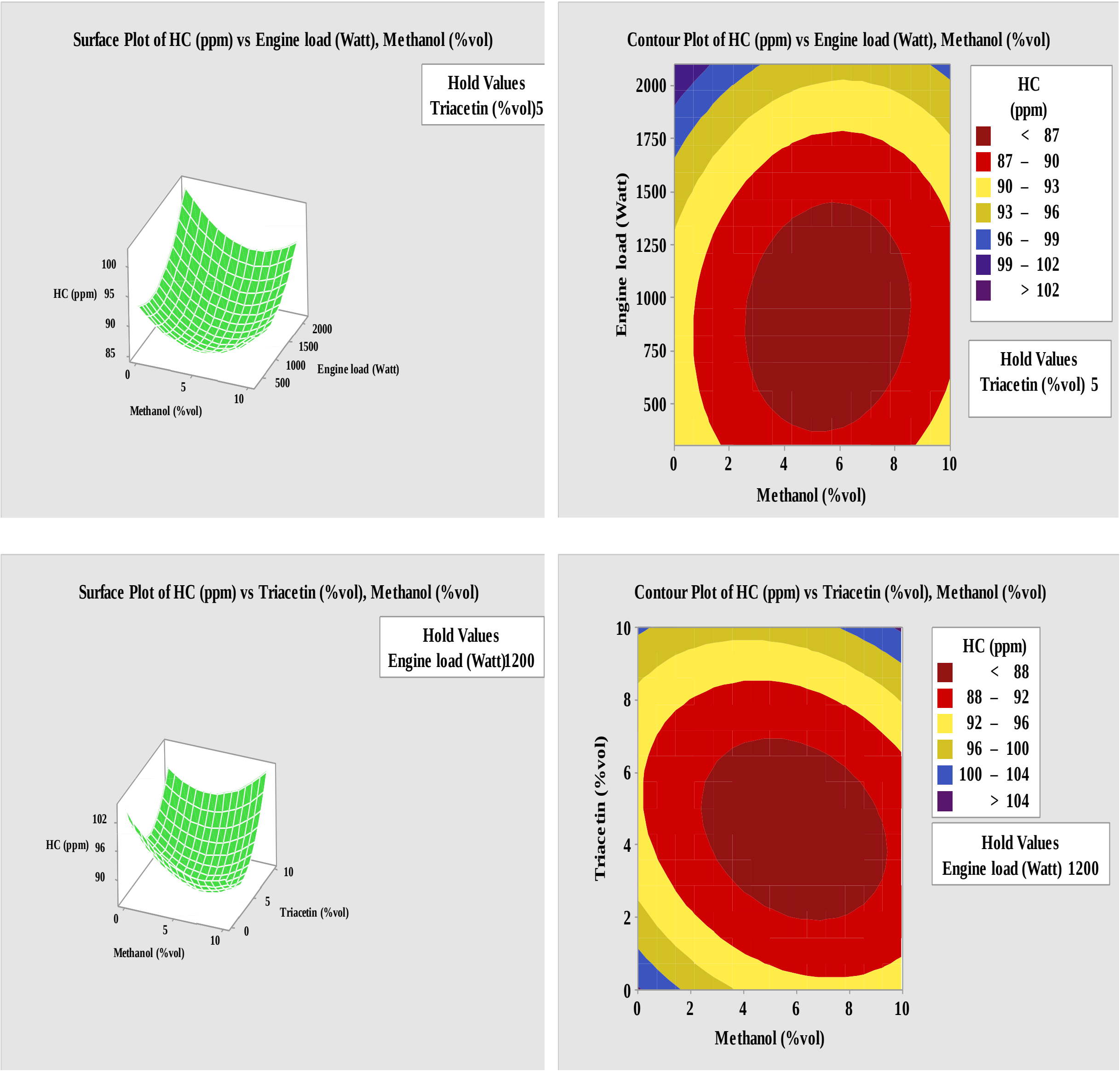
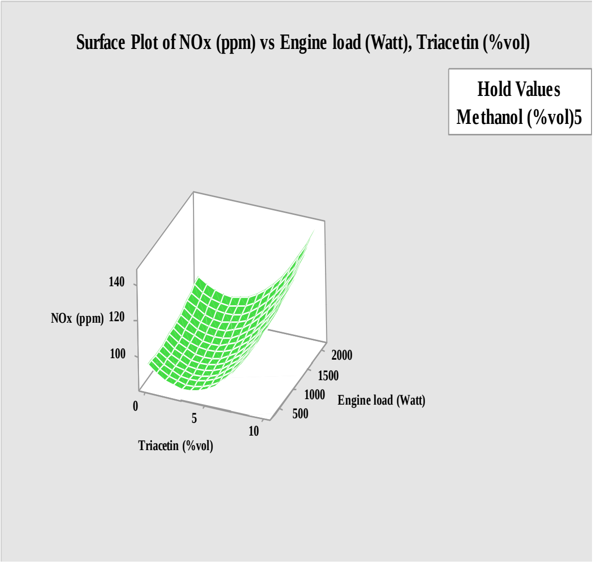


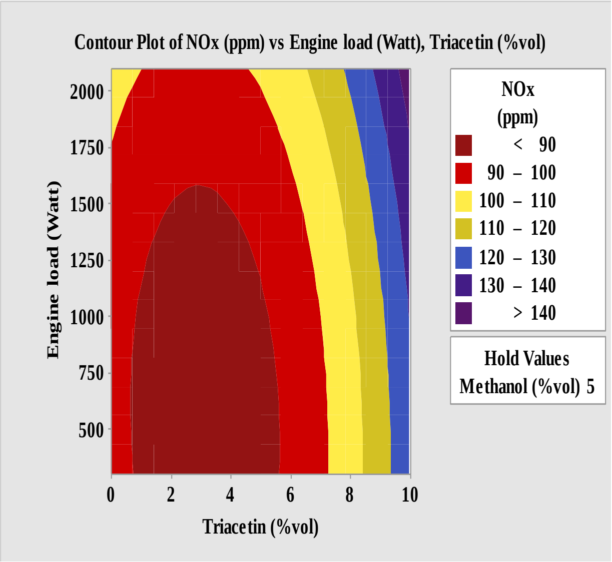
Figure 4.4. Interactive effects of Methanol, Triacetin and Engine load on HC emissions

4.4.1.5 NOx emissions

The combined effect of the concentration of Methanol, Triacetin in the fuel blend, and engine load on the formation of NOx emissions is shown in figure 4.5. It can be clearly seen that at a constant concentration of Methanol i.e. 5 (%vol) and constant engine load i.e. 1200 Watt, the increase in triacetin amount up to 5 (%vol) shows a significant reduction in NOx emission formation. This might be due to the higher latent heat of vaporization and lower calorific value of the triacetin which reduces the temperature of exhaust gas, hence reducing the chance of formation of thermal NO. With further increasing the amount of Triacetin, the NOx emissions tend to increase. This is due to, the higher concentration of oxygen, present in the triacetin molecules, which helps in the formation of NOx emissions.

On the other side, at a constant concentration of triacetin in the fuel blend, on increasing the share of methanol up to 5 (%vol), the formation of NOx emissions tends to decrease. This is due to, higher heat of vaporization and lower heating value of the methanol, which reduces the inside cylinder temperature. With further increasing the dosage of methanol in the fuel blend, the NOx emissions tend to increase. It is because, when the combustion process is closer to stoichiometric, the flame temperature tends to increases [24].





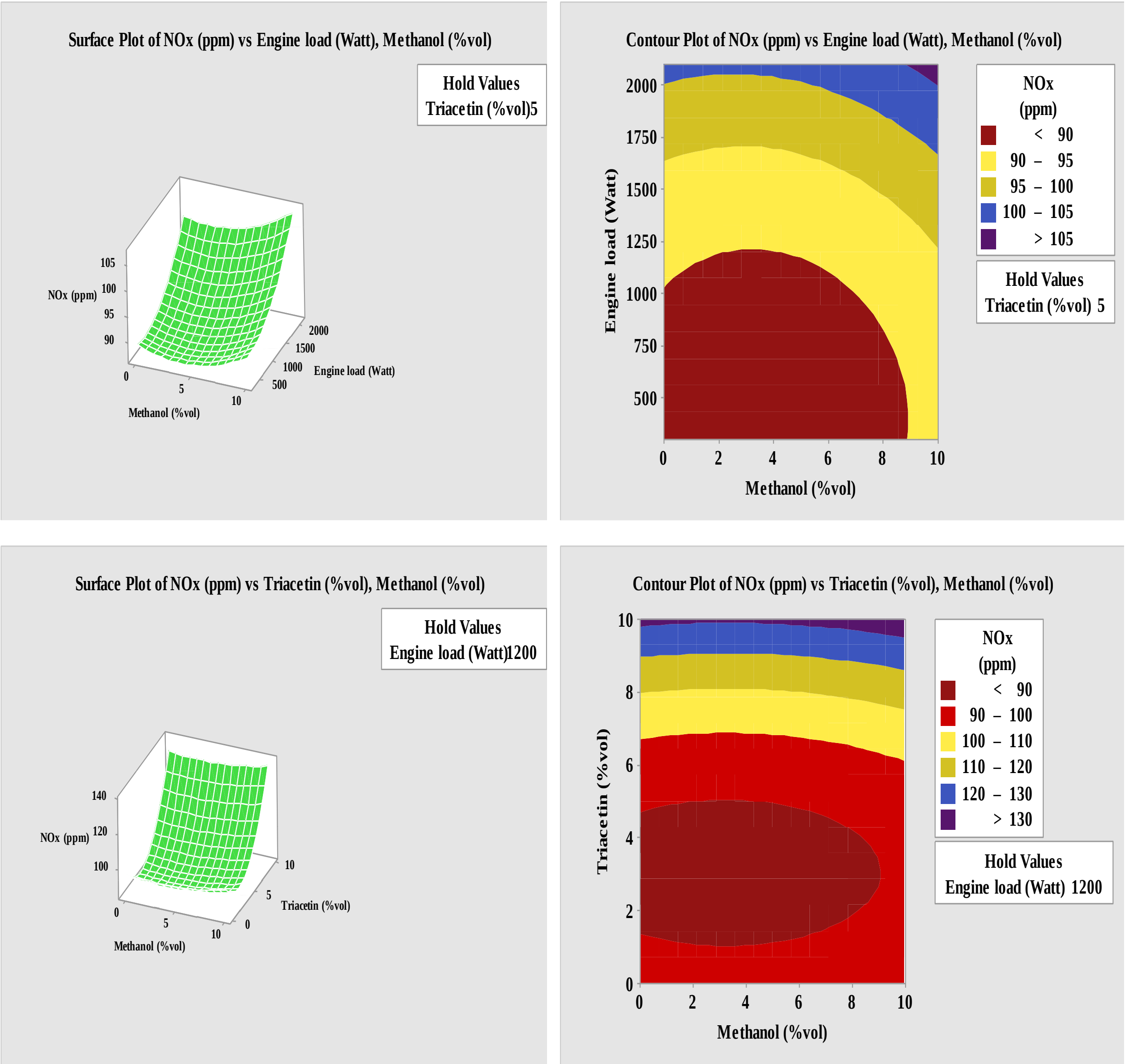


Figure 4.5. Interactive effects of Methanol, Triacetin and Engine load on NOx emissions

4.5. Optimization and Validation

The main objective of the optimization is to find out the optimal values of the concentration of Triacetin, Methanol in the fuel blend, and engine load, for minimizing the CO, HC, NOx, and maximizing the BTE, EGT. The process of optimization is generally regulated by the desirability parameter in which its prime objective function is lies within the range of 0.0 to 1.0 [64]. Table 4.9 enlists the criteria which are employed for achieving the minimum values of engine exhaust emissions with maximizing the engine performance parameters. In the table, the goal for the responses, lower and upper limits for the responses and input factors, the importance of the factors are given. The importance values for the various responses can be varied from 1 to 5. These values indicate the significance level from minimum to maximum. With the help of Minitab17 software, an optimization plot is portraying in figure 4.6, which illustrates the outcomes of the RSM optimizer. It can be observed that the maximum desirability of 0.95 is found for the optimal values of the input factors. The optimal values of the BTE, EGT, CO, NOx, HC, are 26.6676%, 300.8079 °C, 0.8386 (%vol), 87.0537 (ppm), 85.2469 (ppm) respectively and the corresponding optimal operating factors of the engine are Methanol (%vol): 6.5657, Triacetin (%vol): 4.1414, Engine load (Watt): 954.5455.

Table 4.9. Principles of Optimisation

Factors	**Boundaries**		**Weight**	**Importance**	**Goal Criterion**
	Lower	**Upper**			
Triacetin (%vol)	0	10	1	5	In range
Methanol (%vol)	0	10	1	5	In range
Engine load (Watt)	300	2100	1	5	In range
BTE (%)	22.31	26.85	1	5	Maximum
EGT (°C)	274	510	1	5	Minimum
CO (%vol)	0.87	1.265	1	5	Minimum
HC (ppm)	84	112	1	5	Minimum
NOx (ppm)	90	150	1	5	Minimum

BTE: Brake Thermal Efficiency; EGT: Exhaust Gas Temperature; CO: Carbon Monoxide; HC: Hydrocarbons; NOx: Nitrogen Oxides.

Hence, this multivariate technique is successfully able to determine the optimal engine operating factors between the experimental values. The best thing about RSM is that it significantly decreases the number of tests which results in saving both time and money. The optimized results need to be confirmed and validated. For this, it was appropriate to carry out 3 tests and determine the mean value from the best values of the fuel mixture ratio and engine load obtained by the RSM. The Confirmatory test results are then compared with model-predicted values. Table 4.10, shows the test results, a percentage error between the prediction of the optimized parameters and test results. The regression models that have been developed, characterizes the experimental data with a fair accuracy of 9%.

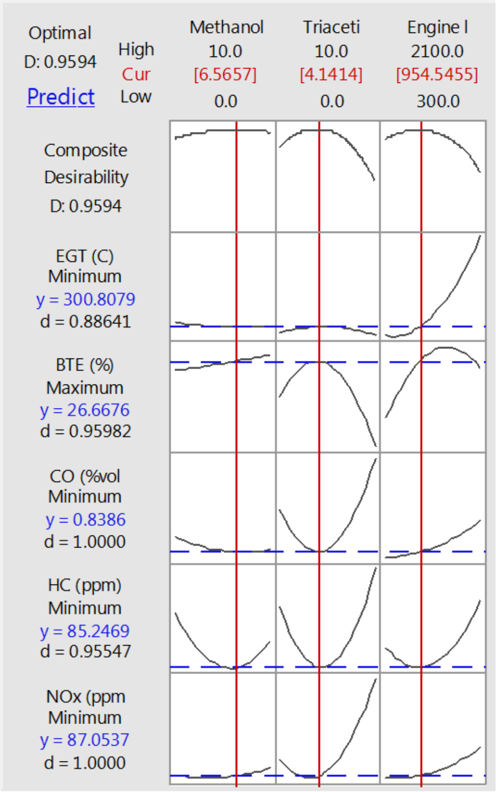


Figure 4.6. Optimization Plot

Table 4.10. Validation tests for experimental and predicted values with percentage error

Fuel Blend	Engine Load (Watt)		BTE (%)	EGT (°C)	CO (%vol)	HC (ppm)	NOx (ppm)
G89.30M6.56T4.14	954.54	Predicted	26.66	300.80	0.83	85.24	87.05
		Experimental	26.37	305.45	0.91	95.03	99.45
		% Error	1.09	1.52	8.79	1.03	1.24

Table 4.11 Comparison between the fuel blends and engine parameters

Fuel Blend	Engine Load (Watt)	BTE (%)	EGT (°C)	CO (%vol)	HC (ppm)	NOx (ppm)
G89.30M6.56T4.14	954.54	26.37	305.45	0.91	95.03	99.45
G100		25.81	318.51	1.01	105.74	110.25

In Table 4.11, the experimental values of the engine performance and emissions parameters are compared with the neat gasoline operation. It can be observed from the table 4.11, on using the optimized value of triacetin additive in the fuel blend, the BTE of the engine can be increased by 2.31%, while EGT value of the engine is decreased by about 4.1%. On the other hand, the engine emissions i.e. CO, HC, NOx are decreased by 9.9%, 10.12%, 9.79% respectively. Hence, on using the optimum combination of the engine operating parameters, the harmful effects on the environment can be reduced.

CHAPTER 5

CONCLUSION

This research work is totally focussed on the utilization of bio-additive (Triacetin) in Gasoline engine that is useful for various purposes. However, from the economic and environment point of view, this approach is critically important and it provides the solutions of two major problems such as: (i) Waste glycerol management which is a major challenge for the biodiesel industries. (ii) Reduce the exhaust emissions by using bio-additive which is derived from glycerol in SI engine.

With the help of attractive results which is shown in this study, following conclusion can be made:

(i) As the ternary mixture of fuel were prepared and has been monitored for a specific period of time. So that, it can be concluded here that, a mixture of Bio-Additive and methanol in gasoline fuel are stable at all atmospheric conditions. No other agents are required to stabilize the fuel blends.

(ii) RSM based optimization studies has carried out for minimizing the exhaust emissions and maximizing the BTE.

(iii) The effects of independent factors i.e. Concentration of Triacetin, methanol in gasoline fuel, and engine load were studied on engine performance and emissions characteristics.

(iv) On the basis of various ANOVA results, all the independent factors had a significant effect on the various responses i.e. BTE, EGT, CO, NOx, HC.

(v) On increasing the concentration of Triacetin (up to 4.14% vol), Methanol (up to 6.56% vol) in the fuel blend and engine load up to 954.54 watts, a total increment of 3.29% in the BTE value was observed as compared to neat gasoline operation.

(vi) At optimal combination of engine operating factors, the exhaust emissions were significantly reduced as compared to neat gasoline operation. An overall reduction of 19.41%, 22.5%, and 17% for CO, HC, and NOx emissions were observed due to the effective combustion in the engine cylinder.

(vii) The values of percentage error for various response variables were obtained from the difference of experimental and predicted values. These values are: 1.09%, 1.52%, 8.79%1.03%, and 1.24% for BTE, EGT, CO, HC, and NOx. All values are lying well within the acceptable ranges.

Hence, with the help of this study various researchers and engine developers can be able to determine the excellent combination of the engine operating factors in order to achieve the desired results by consuming less time This, provides the gateway for improving both the economy and environment.

APPENDIX 1

DENSITY

Measurement range	Density: 0.0gm/cm^3 to 3.0gm/cm^3 Pressure up to 10 bar (145 psi) Temperature: 32°F to 212°F (0°C to100°C)
Repeatability s.d.	Density: 0.000005 gm/cm^3 Temperature: 0.01 °C
Reproducibility s.d.	Density: 0.00002 gm/cm^3
Tables and functions	Tables of Alcohols, Sugar/extract table Tables of acid and bases Twenty programmable user/table functions (Linear function, polynomials, tables)
Accuracy	Density: 0.00005 gm/cm^3 Temperature: 0.03°C
Time taken for one sample	30 seconds (0.5 min)
Power supply	AC 100 to 240 V, 50Hz, 190.0 VA
Size of Machine (L×W×H)	495.0 mm*330 mm*230mm
Weight of Machine	49.60 lbs (22.50 kg)
Data memory	1000 measurement results (optional ring memory)

APPENDIX 2

VISCOSITY

Ranges of Viscosity	0.30 mPa.s to 10,000 mPa.s
Accuracy	up until 0.50%
Repeatability s.d.	up until 0.10%

Time for measurement

Resolution	0.001 seconds
Accuracy	0.50%

Temperature

Temperature range	+ 5°C - 100°C
Accuracy	0.02°C
Repeatability s.d.	0.005°C

Other specification

Volume of sample	0.1 mL to 0.9 mL
Duration of Test	minimum 30 seconds, almost 3min
Accuracy	0.1°
Inclination	15° to 80° in 1° steps
Repeatability s.d.	0.02°
Shear rate	0.5 s^{-1} – 1000 s^{-1} influenced by Inclination and size of capillary

APPENDIX 3

6100 OXYGEN BOMB CALORIMETER CONTROLLED BY AUTOMATIC MICROPROCESSOR

The 6100 Oxygen Bomb Calorimeter which is controlled by the automatic microprocessor is a small-sized, stationary jacket calorimeter that works at nearly about ambient temperature taking maximum advantage of modern microprocessor capabilities. In the 6100 Automatic Compensated Jacket Bomb Calorimeter, the microprocessor controller can automatically control the temperature of the jacket and execute the required error adjustments in real-time. The requirement of less water, energy, and hardware are the most attractive benefits of this system, also it maintains the precision level up to the highest mark. This model uses the conventional designs of the removable bucket and bomb. With a reasonable price, this combination can be used effectively for waste & refusal disposal work, coal testing, and another sample testing.

Technical specification

Model Number	6100
Test/Hour	4-7
Operator time/Test	6 minutes (360 seconds)
Temperature Resolution	0.00001°C
Type of Jacket	Continuously Compensated
Oxygen fill	Automatic
Washing of Bomb	Manual

Filling of Bucket	Manual
Memory	1000 tests
Bomb Model Options	1108, Alloy 20, 1108CL, Alloy G30 1108B, Alloy 20, 1108BCL, Alloy G30 1108BP, Alloy 20, 1109A, 22mL Semi-micro Bomb, 1104, High Strength Bomb
Printer Communication	USB Port
Balance Communication	USB Port
Network Connection	TCP/IP via Ethernet
Size (in cm)	57w x 40d x 43h

APPENDIX 4

SINGLE-CYLINDER AIR-COOLED GASOLINE ENGINE

The detailed specification of the gasoline engine is given in the following table.

Model Name	**Honda EXK 2800**
Number of Cylinder	One
Number of strokes	Four
Ignition System	Transistor Coil Ignition System
Fuel tank capacity (L)	15.5
Cooling System	Forced Air
Rated output (kVA)	2.1
Continuous Running hours (hrs.)	8.2
Dimension (L*W*H) (mm)	985*471*723
Dry Weight (kg)	94
Fuel Gauge	Yes
Oil Alert	Yes

APPENDIX 5

SPECIFICATION OF AVL-DIGAS 1000 BL

Miscellaneous	
Operating Temperature	5°C - 40°C
Humidity	10%-90% non-condensing
Warm uptime	2 min (approx.)
Dimensions (W*H*D)	344*252*85
Storage Temperature	0°C-50°C
Weight	2.20 kg
Certification	2004/22/EC (MID); OML R99 Class 0
Interfaces	USB, Bluetooth class 1, RS 232 (AK Protokoll)

Measured Quantity	**Measuring**	**Resolution**	**Accuracy**
CO	0-15 (%vol)	0.01 (%vol)	< 10.0 (%vol): ±0.02 (%vol)., ±3% o.M. ≥ 10.0 (%vol): ±5% o.M.
HC	0-30 (ppm)	≤ 2.000:1 ppm vol.	< 2000 ppm vol.: ±4 ppm vol., ±3% o.M. ≥ 5000 ppm vol.: ±5% o.M. ≥ 10000 ppm vol.: ±10% o.M.
NO (optional)	0-5.000 ppm vol.	1 ppm vol.	±5 ppm vol., ±1% o.M
O_2	0-25 (%vol)	0.01 (%vol)	± 0.02 (%vol.), ±1% o.M

Power Supply	
Supply of Voltage	Via AVL DITEST CDS Basic Unit: 11.25V DC
Consumption of Power	20 VA (Approx.)

APPENDIX 6

SYSTEM REQUIREMENTS FOR OPTIMISATION SOFTWARE AND ITS DETAILS

SYSTEM REQUIREMENTS (WINDOWS)	
Operating System	Windows 10
RAM	64-bit, 4 GB of memory
Processor	AMD A6-9220 RADEON R4, 5 COMPUTES CORES 2C+3G, 2.50 GHz
Hard disk space (available)	62.4 GB, 2GB (recommended)
Screen resolution	1366 × 768
Connectivity	An internet connection is required for activation of trail and single user licenses
Browser	A web browser is required for Minitab help, Google Chrome (recommended)
Additional software requirement	Microsoft Visual C++ Redistributables for Visual Studio 2007

Details of Software	
Name of Software	MINITAB
Software Version	17.1.0.0

Developers	Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner

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LIST OF PUBLICATIONS

(1) Research Paper titled “Potentails of Waste Plastic Pyrolysis Oil as an Extender fuel for diesel engine”, Mukul Tomar, Prashant Chandra Pujari, Amit Jain,Hansham Dewal, Naveen Kumar. Accepted, Arabian Journal of Geosciences, Springer nature. DOI: 10.1007/s12517-020-05574-6.

(2) Research Paper titled “Optimization of SI engine characteristics fueled with oxygenated bio-additive (Triacetin) using Response Surface Methodology”,Mukul Tomar, Hansham dewal, Ankit Sonthalia, Naveen Kumar. Under peer review: Part E: Journal of Process Mechanical Engineering, Proceedings ofthe Institution of Mechanical Engineers. (Under Review)

(3) Research Paper titled “Potential of waste glycerol derived bio-propanol as an extender fuel for CI engine”, Mukul Tomar, Ankit sonthalia, Hansham Dewal, Naveen Kumar. Under peer review: Environmental Progress and Sustainable Energy, American Institute of Chemical Engineers (AIChE). (Under Review)