

The Effect of TiO₂ Nanoparticle Blended Water Diesel Emulsion Fuel on CI Engine Performance and Emission Characteristics

A Dissertation submitted
in partial fulfilment of the requirements
for the degree of

Master of Engineering
in
Thermal Engineering



By

Rajwinder Singh
Registration No.: 801483019

Under the Supervision of

Mr. Sumeet Sharma
(Associate Professor)
Mechanical Engineering
Department

Dr. D. Gangacharyulu
(Professor)
Chemical Engineering
Department

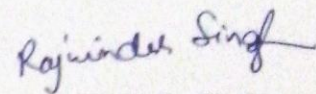
MECHANICAL ENGINEERING DEPARTMENT
THAPAR UNIVERSITY, PATIALA

JUNE 2016

CERTIFICATION

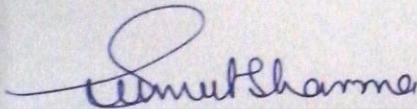
I, Rajwinder Singh, declare that the thesis entitled "The Effect of TiO₂ Nanoparticle Blended Water Diesel Emulsion Fuel on CI Engine Performance and Emission Characteristics" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering in Thermal Engineering** at **Thapar University, Patiala** under the supervision of Mr. Sumeet Sharma, Associate Professor, Mechanical Engineering, Thapar University, and Dr. D.Gangacharyulu, Professor, Chemical Engineering, Thapar University, Patiala during July, 2015 to June, 2016. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

Date: 30/6/2016
Place: Patiala

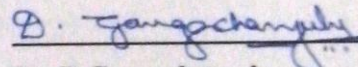


Rajwinder Singh
801483019

It is certify that the above statement made by the student is correct to the best of our knowledge and belief.

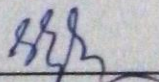


Mr. Sumeet Sharma
Associate Professor
Mechanical Engineering
Thapar University, Patiala - 147004

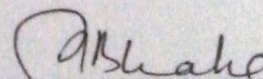


Dr. D.Gangacharyulu
Professor
Chemical Engineering
Thapar University, Patiala - 147004

Countersigned by



Dr. S.K. Mohapatra
Sr. Professor and Head
Mechanical Engineering Department
Thapar University, Patiala - 147004



Dr. S.S. Bhatia
Dean of Academic Affairs
Thapar University, Patiala - 147004

*Dedicated to my parents and my sister
for their love, endless support &
encouragement*

ACKNOWLEDGMENT

I thank God for His abundant blessings in my entire life endeavour.

I owe my deepest gratitude to my supervisor Assoc. Prof. Sumeet Sharma, Department of Mechanical Engineering, Thapar University, Patiala, and co-supervisor Prof. D. Gangacharyulu, Department of Chemical Engineering, Thapar University, Patiala for their constant support, guidance, and motivation throughout my research work. I am very much thankful to them for their precious time and scientific suggestions. It was a privilege to work under their guidance and I am very proud of being their student.

I sincerely thank Head of Mechanical Engineering Department, Thapar University, Patiala and Director, Thapar University, Patiala for providing the necessary experimental facilities during the research work.

I am grateful to Mrs. Harkirat Kaur for their immense help. I would like to extend this thanks to the administrative staff of the Department of Mechanical Engineering for their help. My thanks also go to the Director and staff members of the SAI lab, Thapar University, Patiala, for providing necessary instrumental facilities.

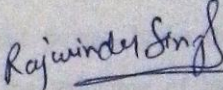
My deep appreciation goes to my classmates for providing a friendly and cheerful environment during my ME. The thesis would not have come to a successful completion, without their help and co-operation. I am highly indebted to all my Classmates. I am also very thankful to my seniors Ajay Kumar and Gurinder Singh for providing me their valuable advices during my research work.

Last, but not least, I would like to dedicate this thesis to my parents and my sister Dr. Ramneek Kaur for their love, patience, and understanding throughout my life. I owe everything to them.

I acknowledge supports from UGC, Govt of India for supporting me financially.

At the end, it is a pleasant task to express my thanks to all the people who made this thesis possible and an unforgettable experience for me.

June, 2016


Rajwinder Singh

Abstract

Environmental degradation due to increase in pollution is the serious problem in the front of the whole world. This problem further deteriorates with the depletion of natural resources. In addition, the fight against the inflation in energy prices and the dependency on the foreign oil has intensified the efforts to develop alternative fuel. Scientists and researchers all over the world are doing their best to develop alternative fuels, which will solve both the problems (pollution and depletion of resources) at the same time. A number of alternative fuels (emulsions, biodiesels etc.) have already been discovered, but most of them are still in research and development sector. Moreover, water-diesel emulsion is viewed more favourable as compared to other alternative fuel due to easy availability of water.

Due to the superior properties of nanofluids, many researchers have examined the impact of various nanoparticles on the performance and emission characteristics of CI engine but most of the current research have been focused solely on nanoparticles dispersed in diesel or biodiesel as base fluid. However, the experimentation done on the emulsion prepared by dispersing water in diesel have shown promising results, hence the effect of nanoparticles in emulsion used as a fuel for compression ignition needs to be studied because experimental data of nanoparticles in diesel and biodiesel had encouraging results.

In the present work, the effect of titanium oxide nanoparticle blended water-diesel emulsion on the performance and emission characteristics of constant speed (1500 rpm) VCR diesel engine are studied. Water-diesel emulsions with 10% and 15% water by volume are used as a base fluid for the addition of 50 ppm and 70 ppm titanium oxide nanoparticles. The mixture of span 80 and tween 80 with Hydrophilic and Lipophilic Balance value of 8 is used as surfactant for the preparation of stable water-diesel emulsion. All the prepared blends (E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50 and E15TiO₂70) are examined at three-compression ratios (14, 16 and 18) with varying loads and the obtained results of performance and emission are compared with that of conventional diesel. All the results are compared and it is concluded that the titanium oxide nanoparticle blended water diesel emulsion not only enhance the performance characteristics (brake power, brake thermal efficiency, brake specific fuel consumption) but also helps in the reduction of harmful emissions from compression ignition engines.

Content

List of Figures	viii
List of Tables	x
Nomenclature	xii
1. Introduction	1
1.1. Compression Ignition Engine Technology	1
1.1.1. Performance Characteristics of CI Engine	2
1.1.2. Desirable Properties of CI Engine Fuel	3
1.2. Need of Alternative Fuels	4
1.3. Emulsion	6
1.3.1. Types of Emulsion	6
1.3.2. Water Diesel Emulsion in CI Engine	8
1.3.3. Effect of Emulsion Fuel on Combustion Efficiency CI Engine	9
1.3.4. Effect of Emulsion Fuel on Emission Parameter of the Engine	9
1.4. Nanotechnology	10
1.4.1. Nanofluids and its Structure	11
1.4.2. Challenges to Nanofluids	12
References	13
2. Literature Review	15
References	26
3. Research Gap and Objective	29
3.1. Gap in Research	29
3.2. Research Objective	30
4. Experimental Details And Methodology	31
4.1. Methodology Adopted	31
4.2. Surfactants Used	32
4.3. Preparation of Fuel	33
4.3.1. Preparation of Water-Diesel Emulsion Fuel	33
4.3.2. Preparation of Titanium Oxide Nanoparticle Blended Water-Diesel Emulsion Fuel	34
4.4. Apparatus Used For Fuel Preparation	35

4.4.1. Magnetic Stirrer	35
4.4.2. Ultrasonicator	36
4.5. Determination of Properties of Emulsion Fuel	37
4.6. Apparatus Used For Evaluation of Fuel Properties	37
4.6.1. Bomb Calorimeter	37
4.6.2. Pensky Martin (Closed Cup) Apparatus	38
4.6.3. The Brookfield Viscometer	39
4.7. Evaluation of Engine Performance Characteristics of Emulsion Fuel	39
4.7.1. Test Setup Used For Experimental Work	39
4.7.2. Performance Parameters Evaluated	42
4.7.3. Experimental Procedure	42
4.8. Evaluation of Engine Emission	43
4.8.1. Equipment Used For The Evaluation of Engine Emissions	43
4.8.2. Procedure to Take Readings	44
5. Results and Discussions	46
5.1. Comparison of Fuel Properties	46
5.1.1. Calorific Value	46
5.1.2. Viscosity	47
5.2. Comparison of Performance Characteristics	48
5.2.1. Brake Power	48
5.2.2. Brake Thermal Efficiency	51
5.2.3. Fuel Consumption	54
5.2.4. Brake Specific Fuel Consumption	57
5.3. Comparison of Emission Characteristics	60
5.3.1. Nitrogen Oxide (NO _x) emission	60
5.3.2. Hydrocarbon (HC) Emission	63
5.3.3. Carbon Monoxide (CO) emission	66
References	70
6. Conclusion and Future Scope	71
6.1. Conclusion	71
6.2. Scope for Future Work	72
Appendix	74

List of Figures

Figure No.	Item Description	Page No.
1.1.	Concept of two-phase (water in oil) and (oil in water) emulsion	7
1.2.	Concept of three-phase (oil in water in oil) and (water in oil in water)	8
1.3.	Concept of micro-explosion phenomenon	10
1.4.	Top-down and bottom up approach	11
1.5.	Nanofluids	12
4.1.	Surfactants used for preparing emulsion fuel	33
4.2.	Surfactant mixture	34
4.3.	Water-diesel emulsion	34
4.4.	CTAB (Surfactant)	35
4.5.	TiO ₂ blended water- diesel emulsion	35
4.6.	Pictorial view of magnetic stirrer	36
4.7.	Schematic view of magnetic stirrer	36
4.8.	Working principle of ultrasonic bath	36
4.9.	Pictorial view of ultrasonic bath	37
4.10.	Pictorial view of bomb calorimeter	38
4.11.	Pictorial view of pensky martin (closed cup) apparatus	39
4.12.	Pictorial view of brookfield viscometer	39
4.13.	Single cylinder, four stroke, variable compression ignition engine	40
4.14.	Schematic diagram of experimental setup	41
4.15.	ACE gas analyser	43
5.1.	Variation in calorific value with the addition of TiO ₂ nanoparticles	47
5.2.	Variation in viscosity of E10 with the addition of TiO ₂ nanoparticles	47
5.3.	Variation in viscosity of E15 with the addition of TiO ₂ nanoparticles	48
5.4.	Variation of bp with respect to load at CR 14	49
5.5.	Variation of bp with respect to load at CR 16	49
5.6.	Variation of bp with respect to load at CR 18	50
5.7.	Variation of bp with respect to load for E10TiO ₂ 70 at CR 14, 16 and 18	50
5.8.	Variation of BTE with respect to load at CR 14	52

5.9.	Variation of BTE with respect to load at CR 16	52
5.10.	Variation of BTE with respect to load at CR 18	53
5.11.	BTE variation for E10TiO ₂ 70 at CR 14, 16 and 18	53
5.12.	Variation of FC with respect to load at CR 14	55
5.13.	Variation of FC with respect to load at CR 16	55
5.14.	Variation of FC with respect to load at CR 18	56
5.15.	FC variation for E10TiO ₂ 70 at CR 14, 16 and 18	56
5.16.	Variation of BSFC with respect to load at CR 14	58
5.17.	Variation of BSFC with respect to load at CR 16	58
5.18.	Variation of BSFC with respect to load at CR 18	59
5.19.	BSFC variation for E10TiO ₂ 70 at CR 14, 16 and 18	59
5.20.	Variation of NO _x emission with respect to load at CR 14	61
5.21.	Variation of NO _x emission with respect to load at CR 16	61
5.22.	Variation of NO _x emission with respect to load at CR 18	62
5.23.	NO _x emission variation for E10TiO ₂ 70 at CR 14, 16 and 18	62
5.24.	Variation of HC emission with respect to load at CR 14	64
5.25.	Variation of HC emission with respect to load at CR 16	64
5.26.	Variation of HC emission with respect to load at CR 18	65
5.27.	HC emission variation for E10TiO ₂ 70 at CR 14, 16 and 18	65
5.28.	Variation of CO emission with respect to load at CR 14	67
5.29.	Variation of CO emission with respect to load at CR 16	67
5.30.	Variation of CO emission with respect to load at CR 18	68
5.31.	CO emission variation for E10TiO ₂ 70 at CR 14, 16 and 18	68

List of Tables

Table No.	Item Description	Page No.
4.1.	Specifications of the surfactant Span 80 and Tween 80	32
4.2.	Specification of Ultrasonic Bath	37
4.3.	Engine Specifications	41
4.4.	Specification of ACE Maxicem 9000	44
5.1.	Brake power (kW) at CR 14, 16 and 18 corresponding to full load	51
5.2.	Brake thermal efficiency (%) at CR 14, 16 and 18 corresponding to full load	54
5.3.	Fuel consumption (%) at CR 14, 16 and 18 corresponding to full load	57
5.4.	BSFC (kg/kWh) at CR 14, 16 and 18 corresponding to full load	60
5.5.	NO _x emission (ppm) at CR 14, 16 and 18 corresponding to full load	63
5.6.	HC emission (ppm) at CR 14, 16 and 18 corresponding to full load	66
5.7.	CO emission (ppm) at CR 14, 16 and 18 corresponding to full load	69
A.1.	Titanium oxide nanoparticle specification	74
B.1.	Various properties of fuels	74
C.1.	Results of BP (kW) for all fuels at different loads and CR 14	75
C.2.	Results of BP (kW) for all fuels at different loads and CR 16	75
C.3.	Results of BP (kW) for all fuels at different loads and CR 18	75
C.4.	Results of BTE (%) for all fuels at different loads and CR 14	76
C.5.	Results of BTE (%) for all fuels at different loads and CR 16	76
C.6.	Results of BTE (%) for all fuels at different loads and CR 18	76
C.7.	Results of FC (kg/h) for all fuels at different loads and CR 14	77
C.8.	Results of FC (kg/h) for all fuels at different loads and CR 16	77
C.9.	Results of FC (kg/h) for all fuels at different loads and CR 18	77
C.10.	Results of BSFC (kg/kWh) for all fuels at different loads and CR 14	78
C.11.	Results of BSFC (kg/kWh) for all fuels at different loads and CR 16	78
C.12.	Results of BSFC (kg/kWh) for all fuels at different loads and CR 18	78
D.1.	Results of NO _x (ppm) for all fuels at different loads and CR 14	79
D.2.	Results of NO _x (ppm) for all fuels at different loads and CR 16	79
D.3.	Results of NO _x (ppm) for all fuels at different loads and CR 18	79

D.4.	Results of CO (ppm) for all fuels at different loads and CR 14	80
D.5.	Results of CO (ppm) for all fuels at different loads and CR 16	80
D.6.	Results of CO (ppm) for all fuels at different loads and CR 18	80
D.7.	Results of HC (ppm) for all fuels at different loads and CR 14	81
D.8.	Results of HC (ppm) for all fuels at different loads and CR 16	81
D.9.	Results of HC (ppm) for all fuels at different loads and CR 18	81

Nomenclature

B

BDC	Bottom Dead Center
BMEP	Brake Mean Effective Pressure
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency

C

CI	Compression Ignition
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CTAB	Cetyltrimethyl Ammonium Bromide

E

E10	2% Surfactant + 10% Water + 88% Diesel (% by vol.)
E10TiO ₂ 50	2% Surfactant + 10% Water + 88% Diesel + 50 ppm TiO ₂ (% by vol.)
E10TiO ₂ 70	2% Surfactant + 10% Water + 88% Diesel + 70 ppm TiO ₂ (% by vol.)
E15	2% Surfactant + 15% Water + 83% Diesel (% by vol.)
E15TiO ₂ 50	2% Surfactant + 15% Water + 83% Diesel + 50 ppm TiO ₂ (% by vol.)
E15TiO ₂ 70	2% Surfactant + 15% Water + 83% Diesel + 70 ppm TiO ₂ (% by vol.)

H

HC	Hydrocarbon
HCV	Higher Calorific Value
HLB	Hydrophilic and Lipophilic Balance

I

IC	Internal Combustion
----	---------------------

N

NO_x Nitrogen Oxides

O

O/W Oil in Water

O/W/O Oil in Water in Oil

P

PM Particulate Matter

S

SI Spark Ignition

SO_x Sulphur Oxides

T

TDC Top Dead Centre

V

VCR Variable Compression Ratio

W

W/O Water in Oil

W/O/W Water in Oil in Water

Greek

Δ Difference

Chapter 1

Introduction

Compression Ignition (CI) engines have a significant role in transportation, agriculture, heavy industries and power generation due to their high power to weight ratio, better fuel economy and low breakdown rate. In spite of the numerous advantages of CI engine over spark ignition (SI) engine, they are also responsible for nearly forty harmful pollutants such as nitrogen oxides (NO_x), unburned hydrocarbon (HC), carbon dioxide (CO_2), particulate matter (PM), carbon monoxide (CO) and sulphur oxides (SO_x) etc [1, 2, 3].

The emission mixture from CI engine contains very small size carbon particles having size less than one micron. These particles combine with hazardous compounds and inhaled into the lungs due to their small size and cause several types of problems like allergies, asthma attack and lung cancer [3]. Further, diesel flumes are more carcinogenic and it is believed that the potential of diesel vehicles exhaust to cause cancer is double as compared to the exhaust from petrol run vehicles.

On an average, a normal human being breathes 22,000 times per day in which he inhales nearly 35 lbs of air [4]. According to annual report of Indian oil, the total utilization of oil in India is 3.3 million barrels per day [5]. From the above-mentioned figures, it is easy to visualize the amount of pollution done by vehicles on a daily basis and the effect of that on human health. According to a new World Health Organization report, Gwalior and Allahabad are second and third largest polluted cities in a list 3000 cities from 100 countries. Whereas Patna, Raipur, and Delhi stand at sixth, seventh and eleventh position, respectively [6].

1.1. Compression Ignition Engine Technology

Compression ignition engine transforms chemical energy of the diesel to mechanical energy. CI engines that are serving the humankind for over 100 years are the most economical IC engines. For the conversion chemical energy into mechanical energy, diesel in atomized form is exposed to high pressure and temperature air. The basic operation of diesel engine is all about producing high temperature and high-pressure air continuously with the help of single slider crank mechanism. When the piston moves from TDC (top dead centre) to BDC

(bottom dead centre), inlet valve opens and fresh air is sucked in. During the return stroke, inlet and exhaust valves are closed as a result the air inside the cylinder is compressed to a compression ratio of about 15:1 to 22:1. During the compression stroke piston does work on the air due to which pressure and temperature of air rises to about 40 bar and 800 K, respectively. Atomized diesel fuel is then injected into the compressed air. Due to high temperature and high-pressure, fuel gets vaporised and undergoes an uncontrolled spontaneous combustion because of which pressure and temperature rises to 150 bar and 2500 K, respectively. This high-energy gas pushes the piston downward from TDC to BDC. Due to the inertia of the system piston moves upward again and reject the combustion gases through the exhaust valve.

The mechanical design of CI engine is challenging task since the combustion process in diesel engine is never uniform and smooth. They are prone to more vibration and noise compared to a petrol engine. Thus, diesel engine requires rigorous structural design.

1.1.1. Performance Characteristics of CI Engine

Engine performance is a relative term, which represents that how well an engine is doing its assigned job. The performance of a CI engine is usually indicated by following factor.

- Brake power developed or BMEP
- Specific fuel consumption (kg/kW-hr)
- Specific power output (kW/kg of engine weight)
- Emission from the engine

A relative importance of these parameters is based upon the applications of the engine. The specific fuel consumption is more important for industrial engines, whereas specific power output is more important for marine engines. Some of the important parameters that are mostly considered in evaluating the engine performance are:

- Indicated power (*ip*)
- Indicated mean effective pressure (*imep*)
- Brake power (*bp*)
- Brake mean effective pressure (*bmep*)
- Volumetric efficiency
- Thermal efficiency
- Emission from the engine

1.1.2. Desirable Properties of CI Engine Fuel

- **Viscosity**

Viscosity is a resistance to flow of liquid as a result of internal friction between the liquid molecules. Optimization of viscosity is very essential because higher viscosity of fuel results into poor atomization of fuel in combustion chamber. Further, more power is required to pump fuel of higher viscosity. On the other hand, lower viscosity results in leakage problem. Therefore, optimum viscosity should be compromised between higher and lower limits [7].

- **Cloud point and Pour point**

Cloud point is defined as the temperature of the oil at which a cloud or haze of wax crystal formed at the base of a test jar when cooled at specific rate. Whereas pour point defined as the temperature, at which fuel stops to flow. Pour point is always lower than cloud point. Cloud point should be small as possible so that this difficulty will not be experienced even in cold weather.

- **Flash point and Fire point**

Flash point is taken as the minimum temperature at which the oil give sufficient amount of vapours, so that the fuel ignites for very short moment. Whereas, the temperature at which vapours are able to burn for more than five seconds is called fire point. The flash point is always lower than fire point by 4 to 9° C. From a safety point of view, this temperature should be high. The flash and fire point indicates the temperature below which, oil can handle without any danger of fire.

- **Volatility**

Volatility affects the ignition quality of fuel. A good quality fuel should have low boiling point components and heavier components in optimum proportion. Low boiling point components helps the engine to start and warm up easily in cold working conditions on the other hand heavier components are required when the engine reaches operating temperature for getting better power and fuel economy. Either too low or too high volatility is not desirable and this leads to improper combustion, effect on fuel injection and vaporization in the combustion chamber, carbon deposits, smoke density and higher hydrocarbon emission. The volatility of fuel required for a particular engine also depends upon its design, size, nature of speed and load variations and atmospheric conditions. For example, more volatile

fuel is required for engines which run in cold weather and involve rapid fluctuation of load and speed, as in the case of buses and trucks.

- **Engine deposits**

The deposits in the engine are a very serious problem. Solid carbon matter is deposited on all parts of engine because of incomplete combustion of fuel. The deposits tend to increase with increasing viscosity and decreasing volatility. Sulphur compounds in the fuel tend to promote both deposits and corrosion. Therefore, low sulphur content is most desirable property of CI engine fuel.

- **Cetane number**

Knocking in CI engine is because of physical and chemical delay period, which is the time lapsed between the injection of the fuel and start of combustion. As the time lag increases, the amount of fuel accumulated increases and abnormal combustion takes place. Therefore, good CI engine fuels should have a low delay period and should ignite more quickly.

1.2. Need of Alternative Fuels

The current state of energy prices and the dependency on the foreign oil has intensified the efforts to develop alternative fuel. The Pollution Conservation Research Association have reported that the transport sector solely accountable for more than 50% of the entire oil consumption in the country. It is found that diesel engine emits forty different types of pollutants, but out of them NO_x , CO, UHC, PM, black smoke, SO_x and CO_2 are emitted in large amounts as compared to others [3]. Increasing stringent regulation on exhaust emissions drives a major research endeavour in engine development in order to reduce these pollutants [4].

From the past several years, research is going on to tackle these problems by providing hardware and fuel based solutions. Modern hardware solutions to control pollution are piezo-injectors, high-pressure fuel injection equipment, exhaust gas recirculation system and diesel particulate filters [9-12]. However, the problem with these systems is that they require modification in the existing engines which is time consuming and costly. On the other hand, fuel based solutions are viewed as a possible as well as economical solution which can solve both the problems (emission and depletion of resources) at the same time. Various fuel-based solutions are:-

- **Biodiesel**

Biodiesel is always considered as a substitute of diesel for CI engines. Biodiesel contains 10% - 15% oxygen by weight, which helps in complete combustion of fuel. This leads to lesser emission from biodiesel engine as compared to diesel fuel [13]. Other advantages of biodiesels are their high lubricating efficiency, higher cetane number, high flash point and very low sulphur content due to which it is also known as sulphur free fuel [14, 15]. In comparison to diesel, biodiesel is more expensive because of high price of plant oil and expensive processing technologies for producing it [16]. Moreover, the heating content of biodiesel is 12% less than diesel on the mass basis. This means for obtaining same engine efficiency, additional fuel is required to burn [13]. Further, they also give rise to the formation of deposits and plugging of filters.

- **Water in diesel emulsion**

Research witnessed that both primary and secondary water-diesel emulsions can be utilised as an alternative fuel for CI engine. Presence of water in the emulsified fuel reduces the adiabatic flame temperature, which brings down NO_x emission. Research shows that the addition of 5% to 20% of water reduces the NO_x emission from 10% to 35%, respectively. Furthermore, the micro - explosion phenomenon helps in better combustion of fuel due to secondary atomization. Fahd et al. [17] had reported the impact of water-diesel emulsion with 10 % water content on 4 cylinder, turbocharged CI engine and results illustrate a reduction in both NO_x and CO emission. Two other methods practiced to inject water into CI engine (other than emulsion) are injection of water in the intake manifold and direct injection of water in combustion chamber with the help of separate injector [12]. Both methods reduce the NO_x emission, but they increase HC and CO emission. Furthermore, they gave rise to oil contamination and engine wear.

- **Nano-fluids**

Advancement of nano science makes it possible to get desired fuel properties by adding nanoparticles/nanotubes into diesel, water-diesel emulsion, and biodiesel. Dispersion of nanoparticles changes the thermo-physical properties of base fluid because of their large surface area to volume ratio, which helps in rapid oxidation process. Metal-based additives also reduce emission from CI engine by producing hydroxyl radicals, which helps in soot oxidation [18-20]. Keshin et al. [21] had experimentally studied the influence of Mg and Mo nanoparticles on the performance and emission parameters of single cylinder DI compression

ignition engine. They observed an improvement in brake thermal efficiency, whereas CO emission and smoke opacity lowered by 56.42% and 30.43%, respectively.

1.3. Emulsion

Emulsion is a colloidal suspension of one liquid into another one or we can say that it is a mixture of two liquids in which one is present as droplets of macroscopic size and distributed throughout the other liquid is called an emulsion. General, the emulsion is prepared by mixing both the parent liquids with or without the help of surface-active agents (surfactants). Surfactants help in increasing the stability of emulsion by weakening the surface tension between the molecules of the constituent liquids. Mechanical agitator is normally used to mix both the liquids. There are three basic conditions that are needed to be fulfilled in order to produce stable emulsion [22]:

1. Insolubility or immiscibility of both the parent fluids with each other is the first and the foremost requirement to produce a stable emulsion.
2. An emulsifier or a mixture of emulsifiers, which weaken the surface tension between the molecules of the constituent liquids, must be present.
3. Adequate agitation must be applied to disperse one liquid into another.

Surfactants weaken the surface tension of base fluid and helps in making stable emulsion. It is found that the mixture of surfactants shows higher stability of emulsion as compared to single surfactant. Surfactants consist of hydrophilic head (polar) and a hydrophobic tail (non-polar). During emulsification, hydrophilic head of the surfactant is oriented towards water, whereas hydrophobic tail orient towards oil, results into a non-adhering film around dispersed droplet.

1.3.1. Types of Emulsion

Classification of emulsion is on the bases of the number of phases present in the emulsion. Further, the number of phases depends upon the emulsification techniques that are used to make an emulsion. Therefore, depending upon the number of phases or type of emulsification techniques, the emulsion is classified into two types: [23]

- **Two-Phase Emulsion:**

The two-phase emulsion is the simplest type of emulsion, which includes one continuous phase and one dispersed phase liquid. Two phase emulsion also known as primary emulsion.

The two-phase emulsion is further classified into oil in water emulsion and water in oil emulsion as shown in figure 1.1.

– **Oil in water emulsions (O/W):**

In case of oil-in water emulsion, oil act as dispersed phase and water act as a dispersion medium (continuous phase). Oil in water emulsion is widely used in food industries for the preparation of a number of food products like homogenized milk etc.

– **Water in oil emulsions (W/O):**

In case of water-in oil emulsion, water act as dispersed phase and oil act as a dispersion medium (continuous phase). Butter is the well-known example of water in oil emulsion. Emulsion fuels, which also came under the category of water in oil emulsion, have shown a number of positive advantages over the conventional fuels.

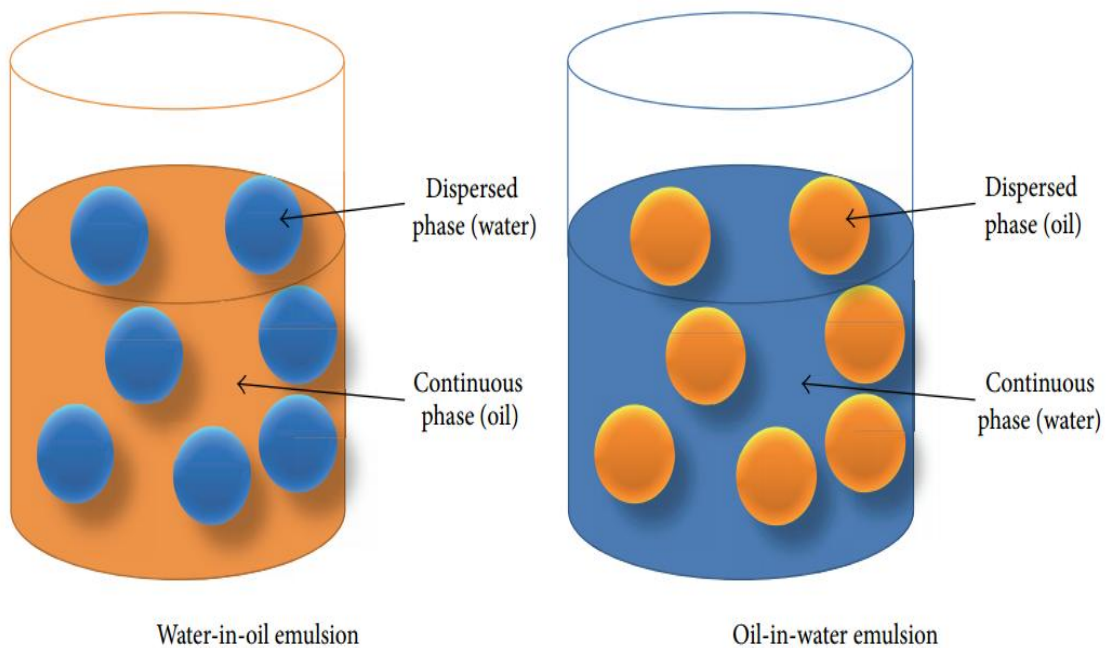


Figure 1.1: Concept of two-phase (water in oil) and (oil in water) emulsion [23].

• **Three-Phase Emulsion:**

Three-phase emulsion consists of one continuous phase and two or more dispersed phases. Three phase emulsions are also known as multiphase emulsion and secondary emulsion. Based upon the inner and the outer phase, three-phase emulsion is further classified into Oil in water in oil emulsion and Water in oil water emulsion as shown in figure 1.2.

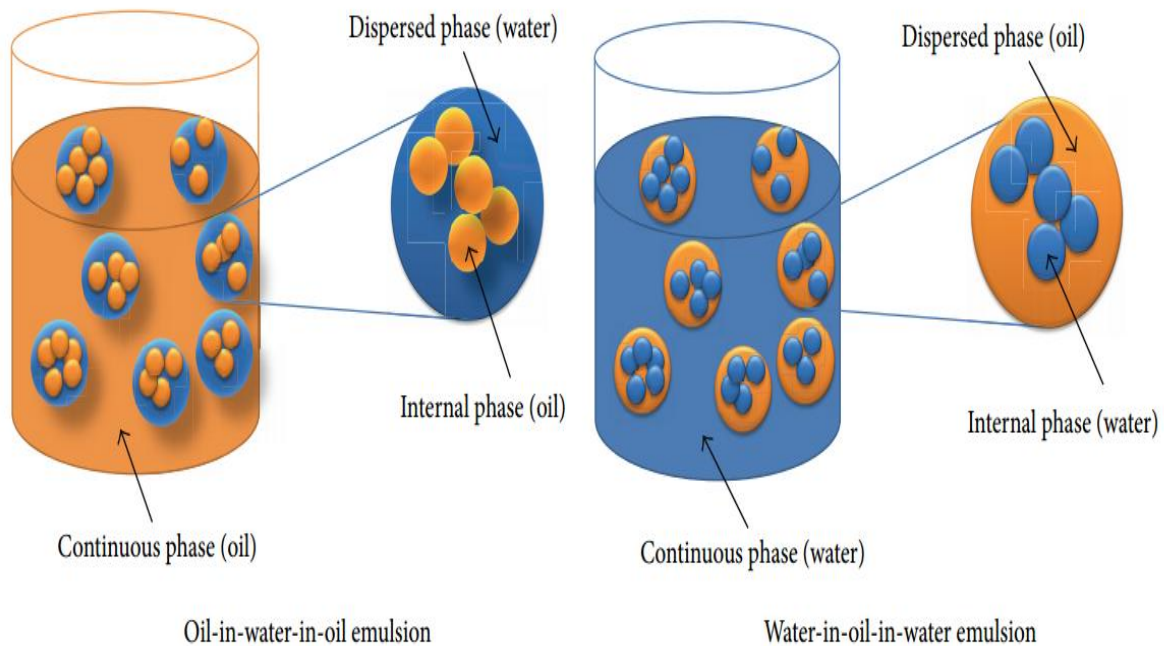


Figure 1.2: Concept of three-phase (oil in water in oil) and (water in oil in water) [23].

1.3.2. Water-Diesel Emulsion in CI Engine

Stringent emission norms and environmental concerns are the prime mover in developing interest in water diesel emulsion. Introducing water into diesel engine shows various convincing effects on exhaust escaping into the environment, which contains nitrogen oxides (including NO and NO₂), particulate matter, hydrocarbon, carbon monoxide and soot. Water diesel emulsions are of more interest due to micro size dispersion of water molecule in diesel fuel, which is desirable for better combustion of fuel. The various triglycerides and light hydrocarbons are used as fuel additives for emulsion fuels [23]. For efficient working of emulsion fuel, the high temperature and pressure is required in a cylinder. Which we get in case of diesel engines and this is the main reason for using water diesel emulsion in diesel engines. Whereas in case of gasoline engines, due to lower compression ratio, pressure and temperature is not favourable for using water-in petrol emulsion as a fuel for spark ignition engine. The main results obtained by using water-in diesel emulsion are:

- Reduction of nitrogen oxide (NO_x) emissions, particulate matter content and soot particles in the exhaust
- Boost combustion efficiency of the engine due to proper combustion of water-diesel emulsion fuel

Nearly, 30% to 40% reduction in the NO_x emission and an appreciable reduction of particulate matters (PM) emissions takes place with the addition of water into diesel. However, we get all the above benefits only with diesel fuel not with other fuels. NO_x emission is the problem with fuels that have high nitrogen content such as some residual oils.

1.3.3. Effect of Emulsion Fuel on Combustion Efficiency CI Engine

Introducing water into the combustion chamber by any kind shows enhancement in the combustion efficiency of the compression ignition engine. As water content up to 20 percent showed an increase in torque over the entire operational range of the engine. When the water in diesel emulsion fuel is injected into the combustion chamber, every single droplet of atomized fuel, breaks into a number of droplets due to a micro explosion phenomenon as shown in figure 1.3. Due to this break up, the surface area that is in contact with air increases, which leads to the improvement in the combustion of fuel. Another basis for the improvement in combustion efficiency is low interfacial tension present in the oil - water compound, promotes better atomization for the burning of injected fuel. Higher contacts with air facilitated due to better dispersion of oil-water molecules and therefore boost the combustion process [23]. It have been suggested that water-in-oil upgrade the combustion phenomenon, leads to the simultaneous overwhelming of droplets, thus providing better mixing of fuel.

1.3.4. Effect of Emulsion Fuel on Emission Parameter of the Engine

The overall temperature inside the cylinder can be reduced by injecting water in CI engine. After the compression stroke, as soon as the emulsion fuel is sprayed inside the combustion chamber, the water particles get vaporized because of high temperature and pressure in the combustion chamber. During vaporization, water takes heat and get converted into steam. This will lower the local high temperature resulting in the reduction of NO_x . Likewise, there is also a micro explosion phenomenon is to facilitate the mixing process which results in reduced reaction time. Further, the reduction in peak temperature lowers the rate of reaction. These combined effects decrease the formation of PM, soot and total hydrocarbon in the exhaust [23].

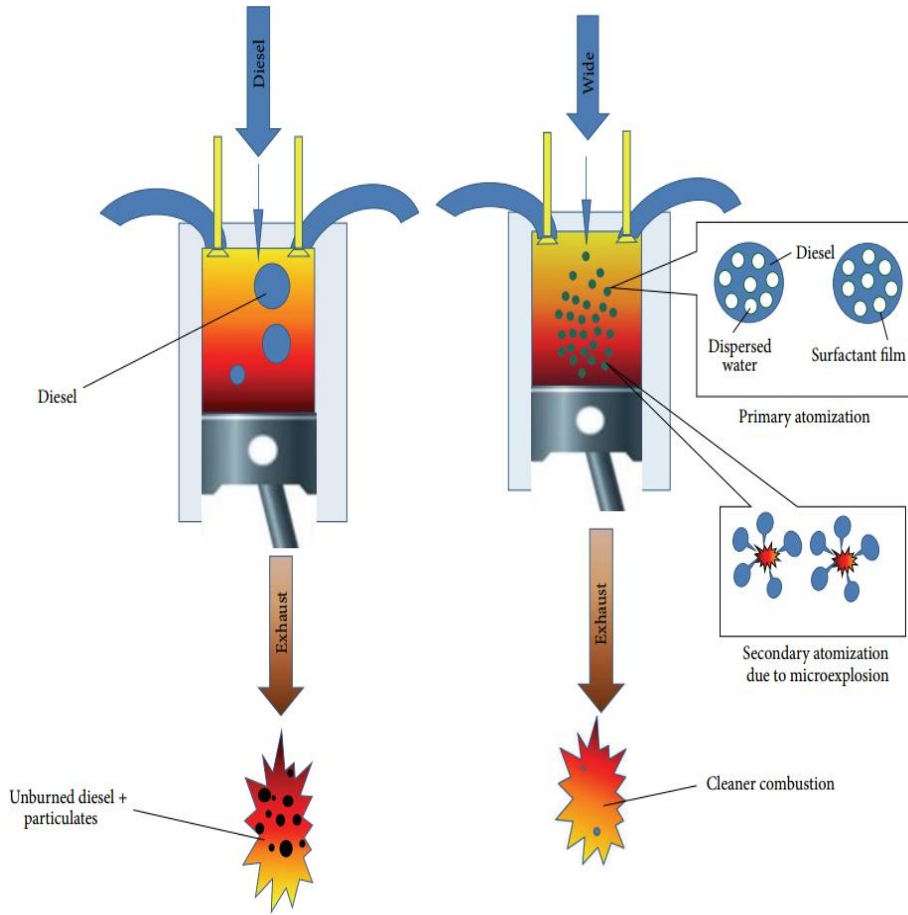


Figure 1.3: Concept of micro-explosion phenomenon [23].

1.4. Nanotechnology

The concept of nanotechnology was initially raised by the Richard Feynman in 1956, in his famous talk, *“There’s Plenty of Room at the Bottom”*. He commented that material can be fabricated by management of individual atoms and the possibility of the production of nanosized products with the use of atoms as building material. The interesting phenomena occurring at the nanometer scale motivate the physicists, chemists, electrical, mechanical and computer engineers for research in nanotechnology for futuristic nanodevices. By changing the size of particles to nanoregion, the range of applications of nanomaterials can be extended. By controlling the features of nanomaterials specially shape and size, it is feasible to boost material properties and device functions, beyond what are earlier established. There are mainly two approaches that are used in nanotechnology as shown in figure 1.4.

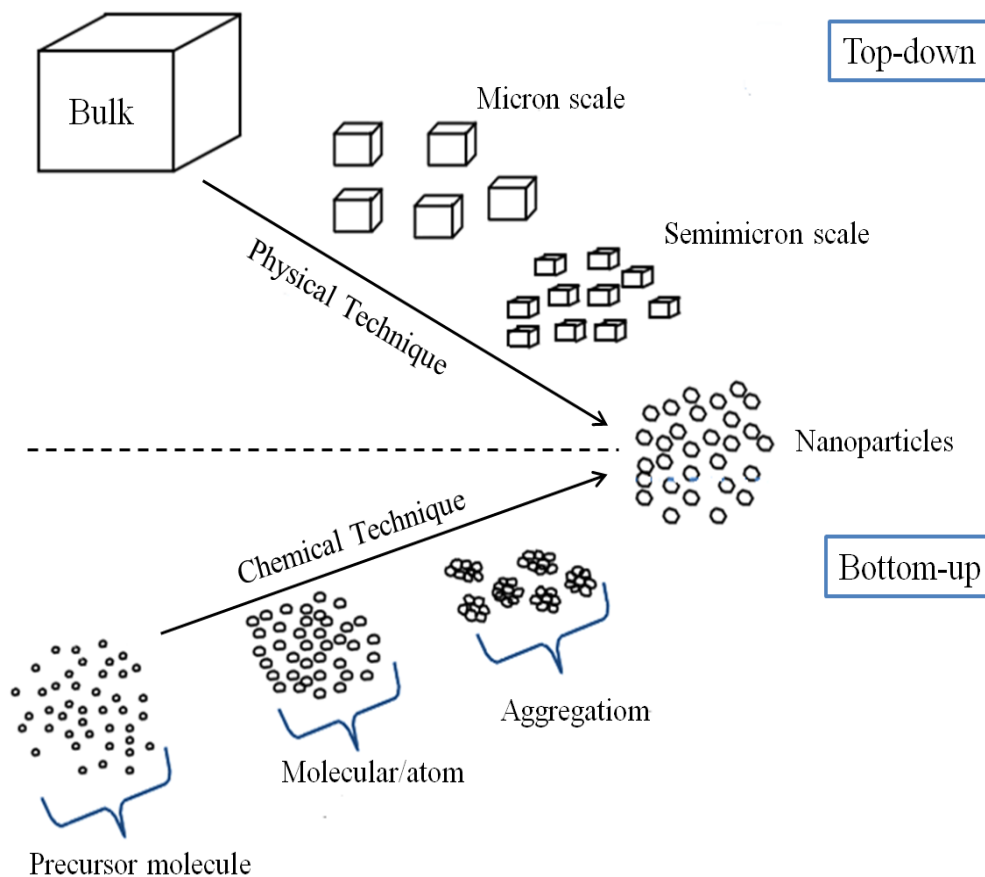


Figure 1.4: Top-down and bottom up approach

– **Top-down approach:**

In top down approach, a bulk material is taken and the size of is reduced to the required nanometer-range by using suitable methods usually physical methods. For example: lithography, ball milling etc.

– **Bottom-up approach:**

In bottom up approach, however, the synthesis process begins at atomic or molecular level. Atoms or molecules of the required material are allowed to assemble till size of the material gets increased to the required size

1.4.1. Nanofluids and its structure

Nanofluids are the heat transfer fluids produced by incorporating the very small size particles (average size less than 100 nm) such as metallic, non-metallic and polymeric into conventional fluid. Yu and Choi, modified Maxwell model with the assumption that the base fluid molecules close to the solid surface of the nanoparticles form a solid-like layered structures. Hence, the nanolayer works as a thermal bridge between the liquid base fluid and

the solid nanoparticles, and this will enhance the effective thermal conductivity [24]. As seen from figure 1.5, a nanofluid consists of the solid nanoparticles, the liquid base fluid and the nanolayers.

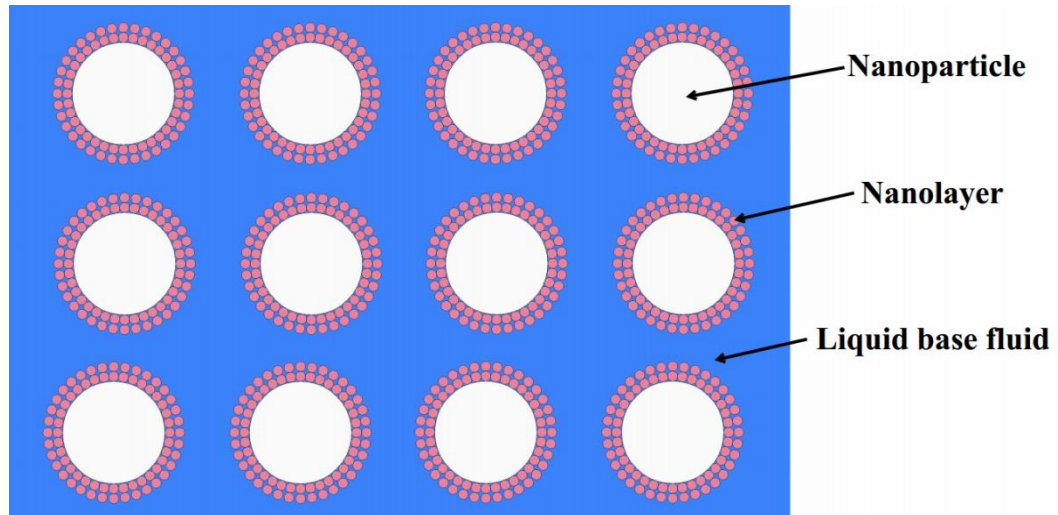


Figure 1.5: Nanofluids

1.4.2. Challenges to Nanofluids

- The cost of nanofluids is very high due to the use of sophisticated equipments for the production of nanoparticles. Nanofluids can either be prepared by one-step method or two-step method.
- Short-term stability of the nanoparticles in the base fluid is also one of the major problems with the use of nanofluids.
- Increase in viscosity with the dispersion of nanoparticles also limits its use under certain conditions.
- Nanofluids also require higher pumping power due change density and viscosity of the base fluid.

References

- [1] C. Lin, The fuel properties of three-phase emulsions as an alternative fuel for diesel engines, *Fuel* 82 (2003) 1367–1375.
- [2] L. Xing-Cai, Y. Jian-Guang, Z. Wu-Gao, H. Zhen, Effect of cetane number improver on heat release rate and emissions of high speed diesel engine fueled with ethanol-diesel blend fuel, *Fuel* 83 (2004) 2013–2020.
- [3] J. Wargo, L. Wargo, N. Alderman, The Harmful Effects of Vehicle Exhaust: A case for policy change, *Environment & Human Health Inc.*, (2006).
- [4] T. Subramani, Study of Air Pollution Due To Vehicle Emission in Tourism Centre, *International Journal of Engineering Research and Application* 2, (2012) 1753–1763.
- [5] D. R. Tobergte, S. Curtis, Indian Oil Annual Report 2014-2015, (2015).
- [6] World Health Organization report, WHO Air Quality Report 2016, May (2016).
- [7] V. Ganesan, Internal Combustion Engine, McGraw-Hill, 4th edition (1994).
- [8] P. Sood, Air Pollution Through Vehicular Emissions in Urban India and Preventive Measures, *Energy and Biotechnology* 33 (2012) 45–49.
- [9] A. Lif, K. Holmberg, Water-in-diesel emulsions and related systems, *Advances in Colloid and Interface Science*, 123 (2006) 231–240.
- [10] T. Kadota, H. Yamasaki, Recent advances in the combustion of water fuel emulsion, *Progress in Energy and Combustion Science* 28 (2002) 385-404.
- [11] O. Armas, R. Ballesteros, F. J. Martos, J. R. Agudelo, Characterization of light duty Diesel engine pollutant emissions using water-emulsified fuel, *Fuel* 84 (2005) 1011–1018.
- [12] J. Ghojel, D. Honnery, K. Al-Khaleefi, Performance, emissions and heat release characteristics of direct injection diesel engine operating on diesel oil emulsion, *Applied Thermal Engineering* 26 (2006) 2132–2141.
- [13] S.D. Kumar, R. Pravin, P. Nikul, Effect of fuel additive on performance and emission for diesel engine fuelled with blend of neem oil biodiesel and diesel, *International Journal of Advanced Engineering Technology* 4 (2013) 66-70.
- [14] A. Demirbas, Progress and recent trends in biodiesel fuels, *Energy Conversion and Management* 50(2009) 14–34.

- [15] M. M. Gui, K. T. Lee, S. Bhatia, Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock, *Energy* 33 (2008) 1646–1653.
- [16] G. Singh, S. Sharma, Performance, Combustion and Emission characteristics of compression ignition engine using nano-fuel: A Review, *International journal of engineering sciences & research technology* 4 (2015) 1034–1039.
- [17] M. E. A. Fahd, Y. Wenming, P. S. Lee, S. K. Chou, C. R. Yap, Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition, *Applied Energy* 102 (2013) 1042–1049.
- [18] W. M. Yang, H. An, S. K. Chou, K. J. Chua, B. Mohan, V. Sivasankaralingam, V. Raman, A. Maghbouli, J. Li, Impact of emulsion fuel with nano-organic additives on the performance of diesel engine, *Applied Energy* 112 (2013) 1206–1212.
- [19] G. R. Kannan, R. Karvembu, R. Anand, “Effect of metal based additive on performance emission and combustion characteristics of diesel engine fuelled with biodiesel,” *Applied Energy* 88 (2011) 3694–3703.
- [20] A. Kumar, S. Sharma, Role of Emulsion and Nanotechnology in Alternative Fuel for Compression Ignition Engine: Review,” *International Journal of Current Engineering and Technology* 4 (2014) 2892–2897.
- [21] A. Keskin, M. Guru, D. Altiparmak, Influence of tall oil biodiesel with Mg and Mo based fuel additives on diesel engine performance and emission, *Bioresource Technology* 99 (2008) 6434–6438.
- [22] G. Chen, D. Tao, An experimental study of stability of oil-water emulsion, *Fuel Processing Technology* 86 (2005) 499–508.
- [23] M. Yahaya Khan, Z. A. Abdul Karim, F. Y. Hagos, A. R. A. Aziz, and I. M. Tan, Current trends in water-in-diesel emulsion as a fuel, *Scientific World Journal* 2014 (2014) 1-15.
- [24] D.K Sarit, C.U.S Stephen, W. Yu, Pradeep, “Nanofluids: Science and Technology,” John Wiley & Sons, Inc. New Jersey (2007).

Chapter 2

Literature Review

This chapter represents the research papers that are studied to formulate the problem. The majority of the research papers are related to preparation of water-diesel emulsion, dispersion of nanoparticles to water-diesel emulsion, effect of nanoparticles dispersed water-diesel emulsion on combustion, performance, and emission parameters of a CI engine.

2.1 Literature Review

Kumar et al. [1] investigated the effect of aluminum nanoparticles on the performance and emission parameters of single cylinder speed well oil engine. Two-phase water-diesel emulsion with 15% water content was used as a base fluid for adding 25 ppm aluminium nanoparticles. Span 80 was utilized to weaken the surface tension between water and diesel. Increase in *bsfc* and brake thermal efficiency was reported at part load due to the addition of aluminium nanoparticles. Both CO and HC emission reduced by 30% and 26%, respectively whereas NO_x emission reduces to 800 ppm from 850 ppm, with the dispersion of nanoparticles.

Mehta et al. [2] experimentally studied the effect of aluminium and nano-silicon blended water diesel emulsion on four cylinder water cooled compression ignition kirloskar engine. Both Aluminium nanoparticles (0.1% by weight) and nano-silicon (0.1% by weight) added (separately) into water-diesel emulsion with 0.5%, 1% and 2% water content. Aluminium nanoparticles blended water-diesel emulsion fuel (W/DA) reduces the *bsfc* by 27% whereas 37% reduction was observed in nano-silicon blended water-diesel emulsion fuel (W/DS). Both W/DA and W/DS increase the brake thermal efficiency by 16% and 14%, respectively. However, in case of NO_x emission, both W/DA and W/DS shows negative effect. Whereas, 4% and 9% reduction was observed in HC with W/DA and W/DS, respectively.

Bidita et al. [3] investigate the effect of surfactant concentrations, water concentrations and cerium oxide nanoparticles on diesel engine. In experiment, different blends of water diesel emulsion of 0.7%, 0.8%, 0.9% and 1% water content was prepared with the help of 0.25%, 0.30%, 0.35% and 0.40% Triton X-100 surfactant (by volume). Concentration of cerium oxide (80 ppm) was held constant during the experiment. Highest reduction of 24% in *bsfc*

was reported in 0.8% water content whereas highest brake thermal efficiency of 37.2% was obtained with 0.40% surfactant concentration. Highest reduction of 61% in NO_x emission was observed with 0.1% water and 0.40% surfactant concentration which can be due to the conversion of CeO_2 to more thermally stable Ce_2O_3 as a result of oxidation of hydrocarbons.

Sadhik et al. [4] investigate the effect of Al_2O_3 blended water-diesel emulsion fuel on single cylinder, DI kirloskar engine. Mixture (2% by volume) of span 80 and tween 80 were utilized to obtain two-phase water-diesel emulsion with 15% water content. Three different concentrations of Al_2O_3 nanoparticles (25 ppm, 50 ppm and 100 ppm) were used in the study. Decrease in BSFC and increase in BTE was observed when Al_2O_3 concentration increases from 25 ppm to 100 ppm. Lower NO_x , HC and CO was observed with 100 ppm concentration of Al_2O_3 .

Gumus et al. [5] experimentally examined the effect of copper oxide (CuO) and aluminum oxide (Al_2O_3) nanoparticles on the physicochemical properties of diesel fuel. Mechanical agitator and an ultrasonicator were used to disperse both aluminum oxide and copper oxide nanoparticles by varying mass fractions. Improvement in flash point and cetane number was observed with the addition of both CuO and Al_2O_3 . The stability characteristics of the prepared nanofuels were also studied under static conditions. Further, the performance and emission parameters of water-cooled, single cylinder diesel engine were investigated. A slight rise in torque and brake power was reported with the dispersion of nanoparticles. On the other hand, a significant reduction in HC, CO and NO_x emission was observed with both CuO and Al_2O_3 blended diesel.

Ramesh et al. [6] had conducted an experiment to investigate the influence of aluminum oxide nanoparticles on combustion, performance and emission parameters of single cylinder, water cooled diesel engine. The nitrogen oxide emission and distribution of temperature inside the combustion chamber was predicted with the help of CFD simulation. A 2D model of diesel engine was created with the help of ANSA CFD software. The aluminum oxide nanoparticle concentration in diesel fuel was varied from 25 ppm to 75 ppm. The reduction in viscosity, shorter ignition delay and better atomization was obtained with the dispersion of aluminum oxide nanoparticles. Further, the reduction in NO_x emission was observed which was also concurred by results obtained from CFD simulation.

Aalam et al. [7] had conducted an experiment on CRDI diesel engine to investigate the effect of iron (*II, III*) oxide on performance and emission characteristics. Mechanical homogenizer and ultrasonic bath was used to mix 25 ppm and 50 ppm iron (*II, III*) oxide nanoparticles having size less than 100 nm. Increase in calorific value and cetane number was observed with the addition of iron oxide nanoparticles. A slight improvement in brake thermal efficiency was also observed. Further, the reduction in HC emission by 48 % and 52 % was observed with 25 ppm and 50 ppm iron (*II, III*) oxide nanoparticles, respectively. The addition of iron (*II, III*) oxide nanoparticles shows negative effect on the amount of NO_x emission. Nearly, 2.2 % and 11.2 % increment in NO_x emission was noticed with 25 ppm and 50 ppm, respectively.

Patil et al. [8] examined the role of HLB value of surfactant mixtures, concentration of surfactant, mixing time, mixing speed and water content on the stability of water diesel emulsion. The one surfactant from span series (Span 20, Span 60, Span 80 and Span 85) and one from tween series (tween 20, tween 60 and tween 80) was mixed in different proportions to get desired HLB (5, 7, 9 and 11) value of the mixture. The above specified surfactants mixtures (1 %, 3 % and 5 % concentration by volume) was used to prepare water diesel emulsion with water content varied from 5 % to 40 % by the step size of 5 %. Water diesel emulsion prepared with the help of 5 % surfactant mixture having the HLB value of 9 showed maximum stability of 30 days. To examine the effect of mixing speed, the rpm of spindle was changed from 3000 rpm to 8000 rpm. Increase in stability was observed with the increase in mixing speed. Further, mixing time was also changed from 5 minutes to 30 minutes with 5 minutes step size. Increase in stability was observed with the increase in mixing time up to certain limit but beyond that stability remains constant. On the other hand, decrease in stability was observed with the increase in water content.

Selim et al. [9] had performed an experiment on Ricardo E6 VCR diesel engine to study the effect of water diesel emulsion fuel on peak cylinder pressure, maximum pressure rise rate, *bp* and *bsfc*. Further, the impact of mixing time, mixing speed and surfactant concentration on the stability of water diesel emulsion were also studied. The amount of water in water-diesel emulsion was varied from 10 % to 30 % by volume. During experiment, engine speed was varied from 18 to 34 rps, load from 2 to 20 Nm and compression ratio from 14 to 22. Nearly four weeks stability was observed for 10 % water in diesel emulsion with 0.2 % emulsifying agent and 2 minutes of mixing time. Whereas, 1 % emulsifying agent and 10 minutes of

mixing time was required to obtain same stability for 20 % water in diesel emulsion. Maximum pressure rise rate was reported to be increased with the dispersion of water. A marginal decrease in brake power and rise in brake specific fuel consumption was occurred with the addition of water. However, this reduction can be tolerated due significant reduction in harmful NO_x emission due to lower peak cycle temperature with the addition of water.

Levitas [10] had examined the effect of heating rate on the burning time of aluminum nanoparticles. Burn time decreases from 1 s to 500 μs with increase in heating rate from 10³ C/s to 10⁷ C/s. The longer burn time at slower heating rate was explained with traditional oxidation mechanism in which diffusion of atoms takes place. However, the fast burning of aluminum nanoparticles at higher heating rate was explained with the help of melt dispersion mechanism. Generally, aluminum nanoparticles are always covered with strong oxide shell. During high heating rate, aluminum core get melts and create hoop stresses in the shell that leads to shell spallation. An unloading wave propagates to the molten aluminum core and creates tensile pressure, which disperse aluminum core in small clusters.

Leng et al. [11] had compared the oxidative thermo-kinetics of milky white emulsion fuel and microemulsion diesel fuel. Water in diesel microemulsion was prepared with the help of rhamnolipid surfactant. The main problem that was observed with milky white emulsion fuel is the separation of water and diesel after the period of two days. On the other hand, microemulsion shows the stability of more than 90 days. The activation energies of both emulsion and microemulsion was compared with that of diesel. Kissinger Akhira Sunose (KAS), Ozawa Flynn Wall (OFW) and Starink's methods was used to predict activation energies. Increase in activation energy by 15 kJ/mol was noticed in case of milky white emulsion whereas the activation energy of microemulsion decreases by 5 kJ/mol which is favourable for shorter ignition delay.

Attia et al [12] had compared the effect of water diesel emulsion fuel structure on the performance and emission of three cylinder turbo charged diesel engine. Two identical samples of water diesel emulsion fuel (17 % water content by volume and 0.5 % surfactant concentration) was prepared with the help of membranes of pore size 0.2 μm and 0.45 μm. It was observed that emulsion fuel prepared with the help of membrane of pore size 0.2 μm (smaller droplet size) produce lower unburned hydrocarbon and smoke level. However, emulsion fuel prepared with the help of membrane of pore size 0.45 μm (larger droplet size) is more effective in the reduction of NO_x emission.

Lin et al. [13] compared the impact of emulsification methods on fuel properties and emission characteristics of two phase and three phase water diesel emulsion. Two-phase (water-diesel) and three-phase (diesel-water-diesel) emulsion was first prepared with the help of mechanical homogenizer and then for the comparison purpose, both the above-mentioned emulsions were prepared with ultrasonic vibrator. It was observed that the emulsions produced by ultrasonic vibrator showed more favourable results such as smaller droplet size of dispersed water, more uniform distribution of water in diesel (continuous phase) and higher stability of emulsified fuel. Further, the emulsion prepared by ultrasonic vibrator showed lower fuel consumption, brake specific fuel consumption and carbon monoxide emission as compared to emulsions produced by mechanical homogenizer. However, higher viscosity of emulsified fuel and larger black smoke opacity was reported in the case of emulsions produced by ultrasonic vibrator.

Sane et al. [14] had examined the effectiveness of water in diesel emulsion in the emission reduction. Multi fuel (diesel and petrol) single cylinder (661 cc), four stroke, water-cooled, VCR engine was used to study the performance and emission characteristics of water in diesel emulsion and diesel. The effect of load and catalytic converter on the emission characteristics was also studied by running the test setup on petrol. Three-way catalytic converter of Maruti Suzuki Alto was attached separately in engine exhaust. Reduction in NO_x and PM emission without any effect on performance was reported with water in diesel emulsion. Moreover, emulsified fuel also showed lower HC emission but only at lower loads. When test setup run on petrol, catalytic converter showed lower HC, CO and NO_x emission corresponding to load.

Lin et al. [15] studied the effect of revolving speed of homogenizing machine, water content, oil content, HLB value of the surfactant mixtures on the properties of water in oil (W/O) emulsion, oil in water (O/W) emulsion, water-oil-water (W/O/W) emulsion and oil-water-oil (O/W/O) emulsion. Water content was varied from 10 % to 30 % in both two-phase (W/O) and three-phase (O/W/O) emulsion whereas oil content was varied from 10 % to 30 % in the case of O/W and W/O/W emulsion. A significant reduction in mean droplet size of O/W/O emulsion was reported with the increase in revolving speed of homogenizing machine. As compared to W/O emulsion, O/W/O showed higher viscosity for same water content. Increase in stability was observed with the increase in HLB value from 6 to 8, but further increase in HLB value showed negative effect on the stability of O/W/O emulsion.

Subramanian [16] investigated the performance and emission characteristics of water- diesel emulsion and timed injection of water into intake manifold of single cylinder, air cooled, CI engine. An electro optical sensor attached to the camshaft to inject water in the intake manifold at proper time. At low loads, highest brake thermal efficiency was obtained with neat diesel whereas full load all the three (diesel, water-diesel emulsion and water injection) showed same brake thermal efficiency. Lower CO and HC emission was reported with water injection but it is also showed higher smoke emission. Reduction in NO_x emission was reported with both (water diesel emulsion and water injection).

Lin et al. [17] examined the effect of various emulsification variables that is HLB value and water content etc on the performance of two phase and three phase emulsified fuel produced by taking biodiesel as a base fluid. Methyl alcohol was mixed with soybean oil to produce biodiesel by transesterification method. Sodium hydroxide was used as catalyst. Further, 10 % water was added with the help of mechanical homogenizer to prepare two-phase and three-phase biodiesel emulsion fuel. Highest stability was reported corresponding to HLB value 13 whereas lowest stability was found with HLB value 6. Higher specific gravity, viscosity and carbon residue was observed with biodiesel emulsion fuel. Moreover, two phase biodiesel emulsion fuel showed smaller mean droplet size and higher heating value than three phase biodiesel emulsion fuel.

Kumar et al. [18] reviewed the literature to understand the influence water /diesel emulsion on the performance and emission characteristics of CI engine. It was observed that water/diesel emulsion is very effective in emission reduction without compromising with performance characteristics. The commercial diesel had reported higher emissions. To overcome this problem, next generation fuel nanofluids were also studied. Nanofluids had shown the higher potential in emission reduction and improvement in performance characteristics. Improvement in combustion efficiency, fuel properties and ignition delay was also reported with the use of nanofluids. A surfactant was reported that it was enhanced the stability of nanofluids. Authors had reported that cerium oxide nanoparticles can utilized with water /diesel emulsion for the enhancement in the performance and emission characteristic on CI engine.

Prabhu et al. [19] examined the influence of titanium oxide nano particle on combustion and emission characteristics of single cylinder diesel engine. Titanium oxide nanoparticles (250 ppm and 500 ppm) were dispersed into diesel blended with 20 % biodiesel. B20 with 250

ppm nano particle showed 1.32% higher brake thermal efficiency in comparison to B20 with 500 ppm. Decrease in CO and HC emission reported with both the blended fuels (B20+250 and B20+500) whereas 5 % higher NO_x emission was also reported in comparison to pure diesel. On the other hand, smoke that is the major problem of diesel engines reduced by 20% for B20 with 500 ppm TiO₂ nanoparticles and by 27% for B20 with 250 ppm TiO₂ nanoparticles.

Mohammed et al. [20] had investigated the effect of CR on diesel engine fuelled with biodiesel. Transesterification process was used to production biodiesel from waste cooking oil that was collected from restaurants. The prepared biodiesel was then blended with pure diesel by 10%, 20%, 30% and 50% concentration by volume. During experiment, the compression ratio was varied from 14 to 18 with the increment of 2. Emission and combustion data obtained from the experiment showed that the increase in compression ratio results into higher engine torque for all the blended fuels as compared to pure diesel. Brake thermal efficiency increased by 18.39%, 27.48%, 18.5% and 19.82% for B10, B20, B30 and B50, respectively as compared to pure diesel. From the emission point of view, biodiesel blends showed nearly 52% reduction in HC emission whereas 37.5% reduction in CO emission was reported when compression ratio was varied from 14 to 18. NO_x and CO₂ emission increase by 36.84% and 14.28% respectively.

Singh et al. [21] reviewed the literature to study the performance and emission characteristics of CI engine using biodiesel with additives as alternative fuel. Biodiesel had not shown significantly improvement in performance, but shown decreasing trend in emission parameters, especially in SO_x, CO and CO₂ except to NO_x. Nanoparticle added fuel improves the emissions and performance of CI engine due to the positive effect of nanofuels on the fuel properties and ignition delay. To improve the performance and emission especially NO_x and particulate matter of diesel and diesel blended with biodiesel nanofuels had become an essential part of today's fuels. From the literature concluded that addition of nanoparticles in diesel and diesel-biodiesel blends not only enhanced the calorific values but also promotes complete combustion due to higher evaporation rates, reduced ignition delay, higher flame temperatures and prolonged flame sustenance. Nanometal oxide additives were reported to be effective in lowering diesel emissions.

Yang et al. [22] evaluated the performance and emission characteristics of four-stroke, DI diesel engine with common rail fuel supply system using water/diesel emulsion as a fuel.

Glycerine was used as fuel additive. Two different concentrations of glycerine (11.5% and 10% by mass) were added to diesel to study the effect of novel nano-organic additives. Concentration of water used for making emulsion oil was 10% and 15%, respectively. Unlike other emulsion fuels, it was transparent with higher stability. Water-diesel emulsion used in the study was transparent and showed high stability. The performance of glycerine blended water diesel emulsion was compared with conventional diesel fuel at various speeds and loads. Decrease in torque with the increase in water content was reported in the results. Emulsified fuel showed improvement in brake thermal efficiency. Especially for E10, brake thermal efficiency of the engine increases by 14.2% as compared to pure diesel. On the other hand, 30.6% reduction in NO_x was observed. Reduction in Combustion duration due to micro explosion phenomenon was also reported.

Yang et al. [23] had conducted the experiment on a 4-cylinder, 4-stroke, CI engine to investigate the effect of water diesel emulsion on the performance and emission characteristics. Polyethoxy-esters and Glycerine were used as oxygenated additives. NP-9 was used as surfactant for higher stability of emulsion. The water droplet size was found to be 100 nm in emulsion oil with a typical diameter of 10 μm . Unlike other emulsion fuel, the emulsion produced in this work was green in colour and was very stable. All the fuels were tested by varying the engine speed and load. Emulsion fuel not only enhance the performance characteristics but also showed significant reduction in NO_x emission. Both hydrocarbon and carbon monoxide emission was reduced for the tested fuels. It was found that the combustion duration was shorter even with the longer ignition delay.

Basha et al. [24] experimentally examined the effect of carbon nanotube (CNT) blended diesel fuel on the performance and emission characteristics of single-cylinder, water-cooled, DI diesel engine with an electrical loading device at constant speed of 1500 RPM. Carbon nanotubes were synthesized by an electric arc discharge method. Concentration of CNT used was 0.5 g/lit, 1 g/lit, 1.5 g/lit by mass fraction. Results were compared with BMEP. Improvement in BTE and BSFC was reported with the addition of CNT blends. The magnitude of emission parameters that is NO_x , CO, HC, EGT and smoke opacity is comparatively less than neat diesel.

Ganesh et al. [25] experimentally examined the effect of jatropha biodiesel with nano fuel additive (B100) on the performance and emission characteristics of single-cylinder, direct injection CI engine running at constant speed of 1500 rpm. Sol-Gel method was used to

prepare Cobalt oxide (Co_3O_4) nanoparticles whereas Al-Mg nanoparticles were prepared by Ball Milling technique. The particle size ranging from 38 nm to 70 nm was obtained in both the methods. Cetyltrimethyl Ammonium Bromide was used as surfactant. Nearly 1% improvement in brake thermal efficiency was observed. The cobalt oxide as additive was more effective in HC emission reduction. Moreover, 47% reduction in NO_x emission was also reported in case of cobalt oxide nano-fuel additive when engine is working at 75% load.

Ajin et al. [26] had conducted an experiment to investigate catalytic activity of cerium oxide nanoparticles. Chemical method was used for the preparation of Cerium oxide nanoparticles. The performance tests were conducted on a naturally aspirated, 4-stroke, single-cylinder, water-cooled, compression ignition engine, operating at 1500 rpm. Surfactant used was dodecyl succinic anhydride, which have HLB Value of 1.34. Cerium oxide nanoparticle (5, 15, 25 and 35 ppm concentration) were dispersed in diesel. Increases in viscosity, flash point and fire point was observed with addition of cerium oxide nanoparticle. Hydrocarbon emission was reduced with the addition of nanoparticle by about 45%, mostly at higher load. Further, 30% reduction in NO_x emission was reported on the addition of cerium oxide nanoparticle in diesel.

Kao et al. [27] had investigated the combustion characteristics of aluminum nanofluid blended diesel. Plasma arc was used for preparing aluminum nanoparticles. The average diameter of nanoparticle was in the range of 40-60 nm. An ultrasonicator was used to produce emulsified nano-aluminum liquid. The aluminum nanofluid (AN) additive was added from 30 cc to 50 cc into 1 litre diesel fuel (D) and then an ultrasonic vibrator was used to vibrate the mixture for 15 min to form the experimental nanoaluminum diesel fuel (AN+D). Combustion curve and emission concentration was determined after 200 sampling combustion cycle. It was observed using AN+D fuel had lowered the BSFC compared with D fuel. For comparison, combustion test at the same condition using pure diesel (D) were also carried out. Results obtained for both the fuels (D and AN+D) over three different engine speeds showed that AN+D is more effective in NO_x emission reduction than D.

Tyagi et al. [28] had done hot plate experiment to study the ignition properties of diesel fuel with the adding of Al and Al_2O_3 nanoparticles to diesel. Various fuel mixtures for the experimental purpose were prepared by varying the concentration of both Al and Al_2O_3 nanoparticles, separately. During each test, 50 droplets were dropped on the top surface of hot plate from a certain height and the number of droplets that ignited was counted to find the

probability of ignition of that fuel. Further, experiments were repeated at different temperatures ranging from 688-768 °C. Higher probability of ignition was reported with the fuels containing that contain nanoparticles.

Huo et al. [29] had study the emulsified diesels with 10% and 20% water by volume because emulsified fuel remains a potential solution to meet the increasingly stringent emission regulations for IC engines due to its capability to reduce both NO_x and PM emissions, simultaneously. The spray and combustion characteristics of emulsified fuel with different blending ratio were experimentally investigated in a constant volume combustion chamber with different injection pressures and under various ambient temperatures. It was found that the surfactant with HLB value of five is relatively the most suitable surfactant composition to the diesel/water interfacial condition. Volumetric density of the water phase bubble size was calculated from micro images revealed that the destabilizing tendency increased with the increasing water content even though W20 still presented a single phase after a 14-day standing. Emulsified diesel manifested longer liquid penetration and longer ignition delay under low ambient temperatures due to the lower volatility of the water. At high ambient temperature, the physical properties of the fuel was weakened; the spread spray cone angles indicated violent breakup events taking place upstream of the spray jet. Applying the intentional over-exposure approach, the liquid phase of the spray was illuminated by the soot incandescence in the broadband luminosity imaging. Glowing spots resulting from disruptive droplet combustion were consistently observed under certain conditions which have resulted from micro-explosion. It was demonstrated that emulsified fuel also affect the primary breakup instead of the secondary breakup under low injection pressure and high ambient temperature conditions. Low injection pressure and higher ambient temperature favour the occurrence of puffing and disruptive droplet combustion at the lift-off as a competition of the micro explosion delay time and primary breakup time. Once the primary breakup timescale is shorter, the micro-explosion may only facilitate the secondary atomization and the glowing spots at the lift-off was fade away.

Khan et al. [30] had reviewed the literature to study the influence of water in diesel emulsion (WiDE) on CI engines performance and emission characteristics. In addition, various methods of emulsion preparation, mechanism behind the working of emulsified fuel and various parameters that affect the properties of emulsified fuel were also studied. The review paper also covers the recent methodologies that were used to examine WiDE for both transport and stationary engine applications. In this review paper, the spray nozzle

arrangement and fuel injection pump was found to be the most critical components as far as the secondary atomization is concerned and further investigation to study the effect of these components on the micro explosion phenomenon of the emulsion was suggested for future.

From the literature review, it is found that water diesel emulsion shows positive effects on both performance and emission parameters of CI engines. Further, dispersion of nanoparticles into diesel or biodiesel, shows enhancement in the properties (Calorific value, flash point etc) and improvement in their performance and emission characteristics.

References

- [1] N.S. Kumar, M.S. kumar, Investigation on the performance and emission characteristics of a diesel engine using water-diesel-nano fluid emulsion as fuel, *Journal of Chemical and Pharmaceutical Sciences* 6 (2015) 37–40.
- [2] R. N. Mehta, M. Chakraborty, P. A. Parikh, Impact of hydrogen generated by splitting water with nano-silicon and nano-aluminum on diesel engine performance, *International Journal of Hydrogen Energy* 39 (2014) 8098–8105.
- [3] B. S. Bidita, A. R. Suraya, M. A. Shazed, M. A. M. Salleh, A. Idris, Influence of Fuel Additive in the Formulation and Combustion Characteristics of Water-in-Diesel Nanoemulsion Fuel, *Energy Fuels* 28 (2014) 4149-4161.
- [4] J. S. Basha, R. B. Anand, An Experimental Study in a CI Engine Using Nanoadditive Blended Water–Diesel Emulsion Fuel, *International Journal of Green Energy* 8 (2016) 332-348.
- [5] S. Gumus, H. Ozcan, M. Ozbey, B. Topaloglu, Aluminum oxide and copper oxide nanodiesel fuel properties and usage in a compression ignition engine, *Fuel* 163 (2016) 80–87.
- [6] K. R. Babu, R. B. Raja, Theoretical and experimental validation of performance and emission characteristics of nanoadditive blended diesel engine, *International Journal of Research in Aeronautical and Mechanical Engineering* 3 (2015) 18–31.
- [7] C. S. Aalam, C. G. Saravanan, B. Premanand, Influence of Iron (II , III) Oxide Nanoparticles Fuel Additive on Exhaust Emissions and Combustion Characteristics of CRDI System Assisted Diesel Engine, *International Journal of Advanced Engineering Research and Science* 2 (2015) 23–28.
- [8] H. Patil, A. Gadhave, S. Mane, J. Waghmare, Analyzing the Stability of the Water-in-Diesel Fuel Emulsion Analyzing the Stability of the Water-in-Diesel Fuel Emulsion, *Journal of Dispersion Science and Technology* 36 (2015) 1221-1228.
- [9] M. Y. E. Selim, M. T. Ghannam, Combustion Study of Stabilized Water-in-Diesel Fuel Emulsion Combustion Study of Stabilized Water-in-Diesel Fuel Emulsion, *Energy Sources* 32 (2015) 256–274.
- [10] V. I. Levitas, Burn time of aluminum nanoparticles: Strong effect of the heating rate and melt-dispersion mechanism, *Combustion and Flame* 156 (2009) 543–546.
- [11] L. Leng, X. Yuana, G. Zeng, H. Wanga, H. Huangc, X. Chen, The comparison of

- oxidative thermokinetics between emulsion and microemulsion diesel fuel, *Energy Conversion and Management* 101 (2015) 364–370.
- [12] A. M. A. Attia, A. R. Kulchitskiy, Influence of the structure of water-in-fuel emulsion on diesel engine performance, *Fuel* 116 (2014) 703–708.
- [13] C. Lin, L. Chen, Comparison of fuel properties and emission characteristics of two- and three-phase emulsions prepared by ultrasonically vibrating and mechanically homogenizing emulsification methods, *Fuel* 87 (2008) 2154–2161.
- [14] H. Sane, N. Purandare, O. Barve, A. Todakar, Emission reduction of ic engines by using water-in- diesel emulsion and catalytic converter, *International Journal of Research in Engineering and Technology* 3 (2014) 378–383.
- [15] C. Lin, K. H. Wang, The fuel properties of three-phase emulsions as an alternative fuel for diesel engines, *Fuel* 82 (2003) 1367–1375.
- [16] K. Subramanian, A comparison of water-diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions, *Energy Conversion and Management* 52 (2011) 849–857.
- [17] C. Lin, S. Lin, Effects of emulsification variables on fuel properties of two- and three-phase biodiesel emulsions, *Fuel* 86 (2007) 210–217.
- [18] A. Kumar & S. Sharma, Role of Emulsion and Nanotechnology in Alternative Fuel for Compression Ignition Engine: Review, *International Journal of Current Engineering and Technology* 4 (2014) 2892–2897.
- [19] L. Prabhu, S. S. Kumar, A. A. K. Rajan, Investigation on performance and emission analysis of TiO₂ nanoparticle as an additive for bio-diesel blends, *Journal of Chemical and Pharmaceutical Sciences* 7 (2015) 408–412.
- [20] M. E. L. Kassaby, M. A. Nemit, Studying the effect of compression ratio on an engine fueled with waste oil produced biodiesel/diesel fuel, *Alexandria Engineering Journal* 52 (2013) 1–11.
- [21] G. Singh, S. Sharma, Performance, combustion and emission characteristics of compression ignition engine using nano-fuel: a review, *International journal of engineering sciences & research technology* 4 (2015) 1034-1039.
- [22] W. M. Yang, H. An, S. K. Chou, S. Vedharaji, R. Vallinagam, M. Balaji, F. E. A. Mohammad, K. J. Chua, Emulsion fuel with novel nano-organic additives for diesel engine application, *Fuel* 104 (2013) 726–731.
- [23] W.M. Yang, H. An, S.K. Chou, K.J. Chua, B. Mohan, V. Sivasankaralingam, V. Raman, A. Maghbouli, J. Li, Impact of emulsion fuel with nano-organic additives on

- the performance of diesel engine, *Applied Energy* 112 (2013) 1206–1212.
- [24] J. S. Basha, R. B. Anand, Performance , emission and combustion characteristics of a diesel engine using Carbon Nanotubes blended Jatropha Methyl Ester Emulsions, *Alexandria Engineering Journal* 53 (2014) 259–273.
- [25] D. Ganesh, G. Gowrishankar, Effect of nano-fuel additive on emission reduction in a biodiesel fuelled CI engine, *Electrical and Control Engineering* (2011) 3453–3459.
- [26] A. C. Sajeevan, V. Sajith, Diesel engine emission reduction using catalytic nanoparticles : An Experimental Investigation, *Journal of Engineering* 2013 (2013) 1-9.
- [27] M. J. Kao, C.C. Ting, B.F. Lin, T.T. Tsung , Aqueous Aluminum Nanofluid Combustion in Diesel Fuel, *Journal of Testing and Evaluation* 36 (2008) 1-5.
- [28] H. Tyagi, P. E. Phelan, R. Prasher, R. Peck, Increased hot-plate ignition probability for nanoparticle-laden diesel fuel, *Nano Letters* 8 (2008) 1410–1416.
- [29] M. Huo, S. Lin, H. Liu, C. F. Lee, Study on the spray and combustion characteristics of water–emulsified diesel, *Fuel* 123 (2014) 218–229.
- [30] Y. Khan, Z. A. A. Karim, F. Y. Hagos, A. R. A. Aziz, I. M. Tan, Current trends in water-in-diesel emulsion as a fuel, *Scientific World Journal* 2014 (2014) 1-15.

Chapter 3

Research Gap and Objective

Environmental degradation due to increase in pollution is the serious problem in the front of the whole world. This problem is further deteriorates with the depletion of natural resources. Moreover, the current state of energy prices and the dependency on the foreign oil has intensified the efforts to develop alternative fuel. Scientists and researchers are doing their best to develop alternative fuels, which will solve both the problems (pollution and depletion of resources) at the same time. A number of alternative fuels (emulsions, biodiesels etc.) have already been discovered, but most of them are still in research and development sector. Further research is going on to enhance the properties of these fuels by the addition of various fuel additives. Moreover, water-diesel emulsion is viewed more favourable as compared to other alternative fuel due to easy availability of water.

3.1. Gap in Research

A plenty of research has been done on emulsion preparation methods, performance and emission characteristics of CI engines by varying the amount of water in diesel. Further, many researchers have reported the effect of various emulsion preparation methods on stability. Moreover, the stability of water diesel emulsion has been studied by changing the amount of surfactants, using different types of surfactants and mixture of two or three surfactants. With the advancement and the advantages of nanofluids, many researchers have examined its impact on the performance and emission parameters of IC engines. From the literature review, it is observed that the impact of nanoparticles on the performance as well as emission characteristics of a CI engine is mostly studied by using diesel and biodiesels as a base fluid for preparing nanofluids. However, a very little research has been carried out to study the effect of nanoparticle as fuel additives in water diesel emulsion on the performance and emission characteristics of a compression ignition engine. Further, no one has examined the effect of titanium oxide nanoparticles blended water-diesel emulsion on the performance and emission characteristics of the VCR diesel engine.

3.2. Research Objective

The literature survey is done to find out the objective of the present work. The major objective of the current work is to do a comparative analysis of water diesel emulsion with and without titanium oxide nanoparticles on the performance and emission characteristics of four stroke, single cylinder, VCR diesel engine. Water-diesel emulsion with 10% and 15% water by volume is used as a base fluid for the addition of 50 ppm and 70 ppm titanium oxide nanoparticles. All the prepared blends are tested and examined at three-compression ratios (14, 16 and 18) with varying loads and the obtained results of performance and emission are compared with that of conventional diesel.

The objectives of the present work are divided into the following parts:-

1. To evaluate the fuel properties.
2. To evaluate the performance characteristics of water-diesel emulsion fuel with and without titanium oxide nanoparticles.
3. To evaluate the emission characteristics of water-diesel emulsion fuel with and without titanium oxide nanoparticles.
4. Comparative analysis of performance and emission characteristics of water-diesel emulsion fuel with and without titanium oxide nanoparticles with diesel.

Chapter 4

Experimental Details and Methodology

In this chapter, the methodologies for the preparation of water-diesel emulsion and titanium oxide nanoparticle blended water-diesel emulsion is discussed. This chapter describes the process for the determination of different fuel properties of water-diesel emulsion and titanium oxide nanoparticle blended water-diesel emulsion samples (E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50 and E15TiO₂70). These six blends were charged into a variable compression ignition diesel engine to analyze its behaviour at five different loads and three different compression ratios. The performance parameters of compression ignition engine such as indicated power, brake power, brake mean effective pressure, indicated mean effective pressure, indicated thermal efficiency, brake thermal efficiency, brake specific fuel consumption and exhaust gas temperature were found with the help of ICEngineSoft software provided by Apex Innovations Private Limited. Whereas, pollutants such as CO, HC and NO_x was analyzed with the help of ACE Maxicem 9000 exhaust gas analyzer. These performances and emission parameters of all the blend of water-diesel emulsion with and without a titanium oxide nanoparticle were compared to those of diesel.

4.1. Methodology Adopted

The complete experimental work was carried out in the following steps:-

1. Preparation of surfactant of desired HLB value with the help of two surfactants: Span 80 and Tween 80,
2. Preparation of water-diesel emulsion fuel,
3. Preparation of titanium oxide nanoparticle blended water-diesel emulsion fuel,
4. Evaluation of fuel properties,
5. Evaluation of performance and emission characteristics of water-diesel emulsion fuel with and without titanium oxide nanoparticles, and
6. Comparative analysis of performance and emission characteristics of water-diesel emulsion fuel with and without titanium oxide nanoparticles with pure diesel.

4.2. Surfactants Used

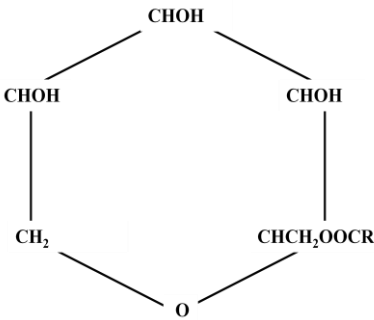
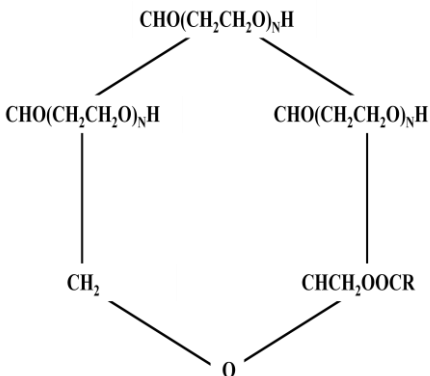
Surfactants help in increasing the stability of emulsion by weakening the surface tension between the molecules of the constituent liquids. It was found that the mixture of surfactants shows higher stability of emulsion as compared to single surfactant. Surfactants consist of hydrophilic head (polar) and a hydrophobic tail (non-polar). During emulsification, hydrophilic head of the surfactant is oriented towards the water, whereas hydrophobic tail orient towards oil, results into a non-adhering film around dispersed droplet.

Span 80 with HLB (hydrophilic lipophilic balance) 4.3 and Tween 80 with HLB 15 are two surfactants that are used in the present work. Specifications of the both the surfactants are shown in Table 4.1. The combined HLB of both the surfactants is 8. The formula used to calculate the HLB value is given as:

$$HLB_{AB} = \frac{(H_A \times W_A) + (H_B \times W_B)}{W_A + W_B} \quad (4.1)$$

Here H_A and H_B represent the HLB values of the surfactant A and B, respectively. Whereas, W_A and W_B represent the weight of the surfactant A and B.

Table 4.1: Specifications of the surfactant Span 80 and Tween 80 [32]

Surfactant Name	Span 80 (Sorbitan Monooleate)	Tween 80 (Polyoxyethylene Sorbitan Monooleate)
Chemical Structure		
HLB	4.3	15
Specific Gravity	0.98	1.08

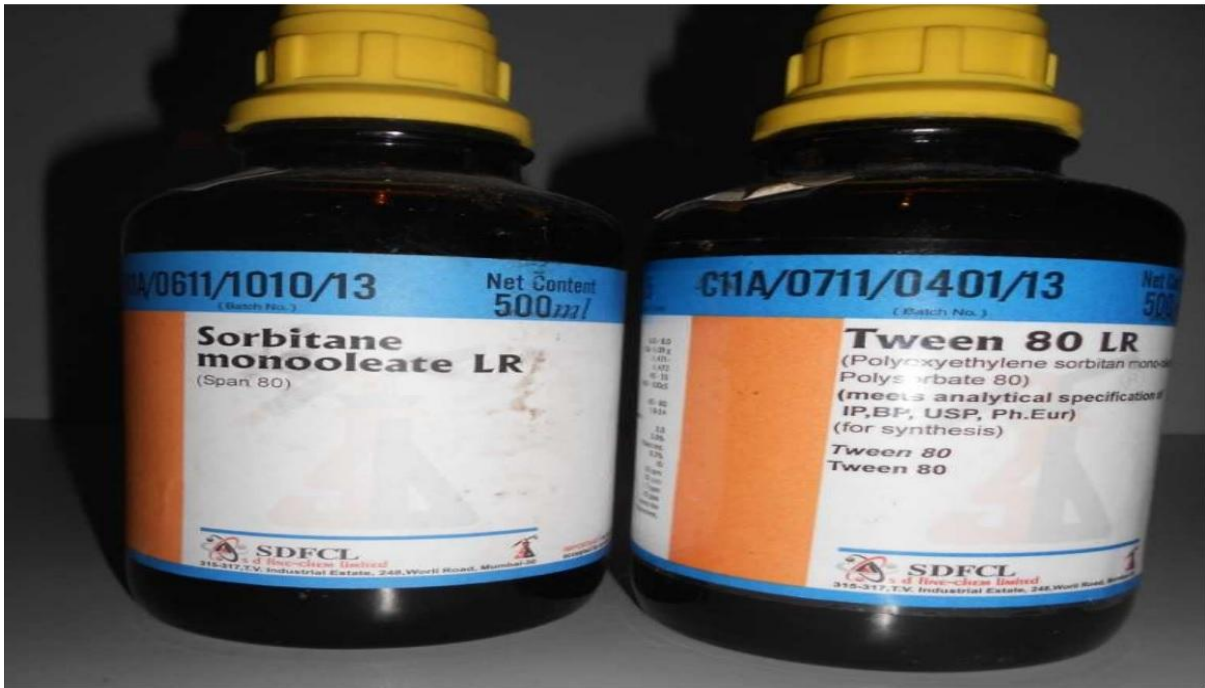


Figure 4.1: Surfactants used for preparing emulsion fuel

4.3. Preparation of Fuel

The preparation of fuel was done in two parts: first, water-diesel emulsion preparation with 10% and 15% water content by volume; second, titanium oxide nanoparticle blended water-diesel emulsion fuel with 50 ppm and 70 ppm nanoparticle concentration.

4.3.1. Preparation of Water in Diesel Emulsion Fuel

water-diesel emulsion fuel was prepared by dispersing 10% water content by volume into diesel fuel. The preparation of water-diesel emulsion was done in three steps:

1. Surfactant mixture (2% by volume) of two surfactants (Span 80 and Tween 80) was prepared to get the desired value of hydrophilic and lipophilic balance of value 8.
2. The prepared surfactant mixture was added into the diesel fuel (88% by volume). After stirring it for 10 minutes with the help of mechanical agitator, add water (10 % by volume) gradually into it and stirrer it for another 30 minutes.
3. In order to achieve higher stability of water-diesel emulsion fuel, the sample was placed in an ultrasonicator for half an hour.

Above procedure was also followed for second blend of water-diesel emulsion fuel with 15% water content.



Figure 4.2: Surfactant mixture



Figure 4.3: Water-diesel emulsion

4.3.2. Preparation of Titanium Oxide Nanoparticle Blended Water-Diesel Emulsion Fuel

Titanium oxide nanoparticles was used to examined the effect of nanoparticle blended water-diesel emulsion fuel on compression ignition diesel engine. Magnetic stirrer and ultrasonicator was utilized for the production nanoparticles blended water-diesel emulsion. Hexadecyltrimethyl ammonium bromide (CTAB) was used as a surfactant for dispersing titanium oxide nanoparticle into water-diesel emulsion. Steps followed in the preparation was:-

- 1.** Hexadecyltrimethyl ammonium bromide (CTAB) surfactant was added into earlier prepared water-diesel emulsion fuel (E10) with the help of magnetic stirrer.
- 2.** Titanium oxide nanoparticle (50 ppm) was added gradually into it and Stirring was done for 30 minutes.
- 3.** Then it was placed in an ultrasonicator for 90 minutes, so that nanoparticle gets properly dispersed into it. The resultant product yields the titanium oxide nanoparticles blended water-diesel emulsion (E10TiO₂50).
- 4.** The same procedure was adopted for adding 50 ppm nanoparticles in E15, 70 ppm nanoparticles in E10 and E15 to yield E15TiO₂50, E10TiO₂70 and E10TiO₂70, respectively.

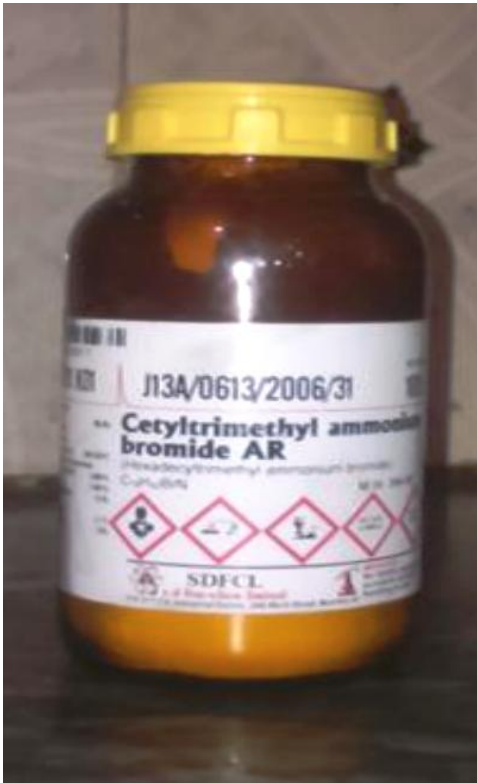


Figure 4.4: CTAB (Surfactant)

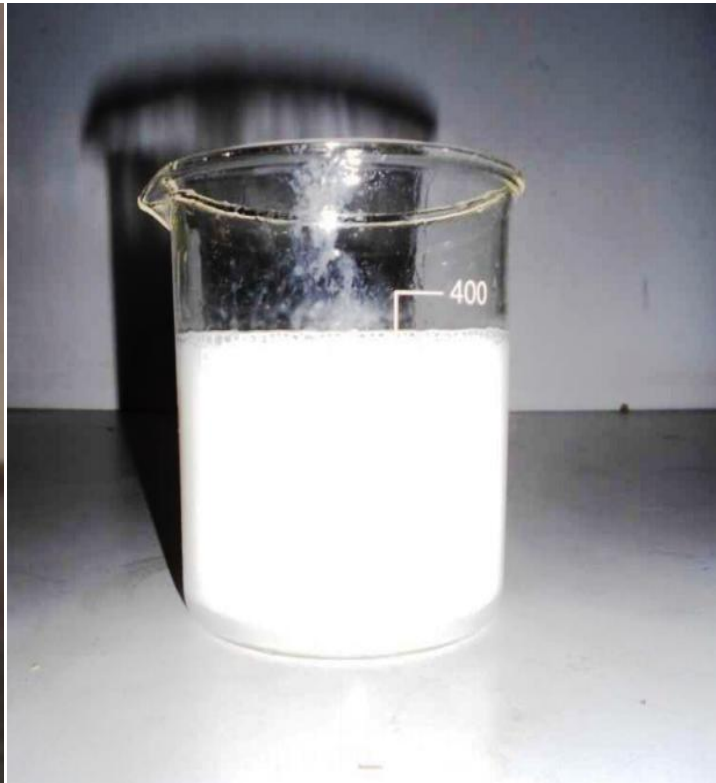


Figure 4.5: TiO₂ blended water-diesel emulsion fuel

4.4. Apparatus Used For Fuel Preparation

The following apparatus was employed for the preparation of water-diesel emulsion and titanium oxide nanoparticle blended water-diesel emulsion.

4.4.1. Magnetic Stirrer

A magnetic stirrer is equipment that utilizes rotating magnetic field to spin magnetic stirbar. The magnetic rotating field can be produced either by a rotating magnet or by a set of stationary electromagnets. Pictorial and schematic view of magnetic stirrer used to prepare water-diesel emulsion is shown in figure 4.6 and 4.7, respectively. Method to use magnetic stirrer is as:-

1. Place the stir bar in beaker containing solution to be stirred.
2. Place the beaker in the centre of the top surface of the stirrer.
3. Adjust the speed with the help of stir control knob.
4. After the desired stirring, turn the stir control knob to off position.



Figure 4.6: Magnetic stirrer

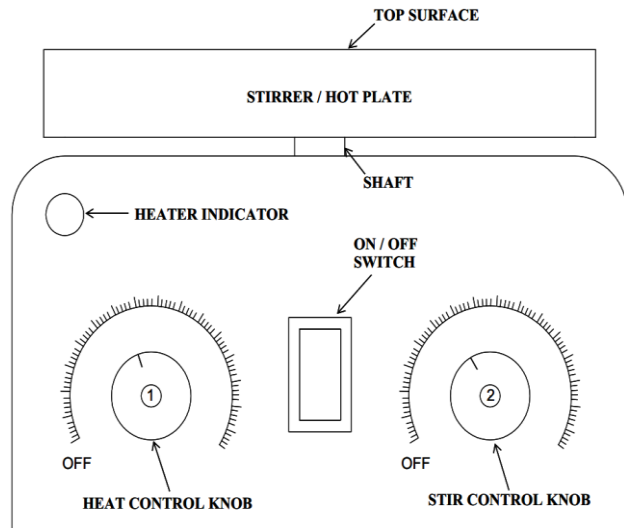


Figure 4.7: Schematic view of magnetic stirrer

4.4.2. Ultrasonicator

BRANSON CPX-3800H (digital with heating arrangement) ultrasonic bath was used to homogenize both water-diesel emulsion and titanium oxide nanoparticle blended water-diesel emulsion. In ultrasonic bath, transducer installed below the steel tank radiates ultrasonic sound waves (frequencies beyond the range of human hearing). When these sound waves travel through the tank containing the solution to be homogenized, alternatively low and high pressure is created in the solution. During low pressure, millions of microscopic bubbles form in the solution. In the next moment, these bubbles collapsed due to high-pressure and release an enormous amount of energy in all the directions (as shown in figure 4.8) which helps in homogenization. This energy can also be used for cleaning, dissolving and degassing. Figure 4.9 shows the pictorial view. Specifications are shown in table 4.2.

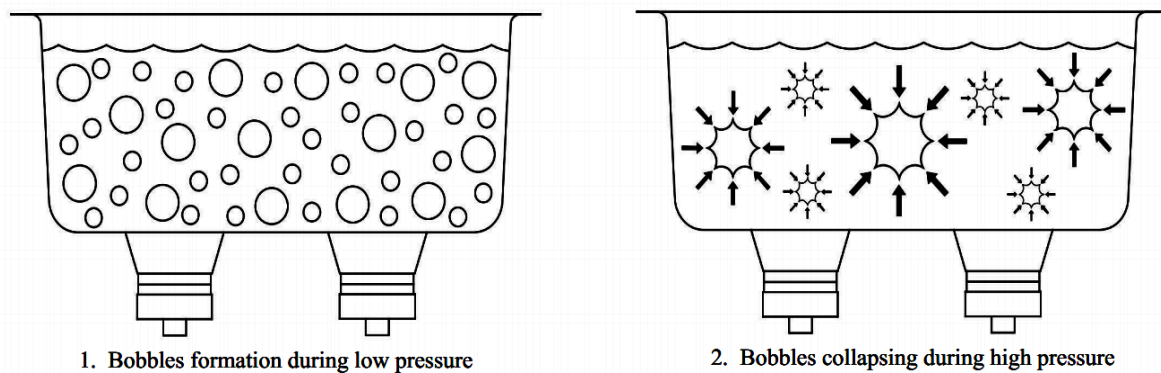


Figure 4.8: Working principle of ultrasonic bath

Table 4.2. Specification of Ultrasonic Bath

Model No.	3800
Type	CPXH
Tank capacity (liters)	5.7
Tank size (mm)	290 X 150 X 150
Frequency	40 kHz



Figure 4.9: Pictorial view of ultrasonic bath

4.5. Determination of Properties of Emulsion Fuel

Evaluation of the following properties of the produced emulsion fuel is discussed below:

1. Calorific value
2. Kinematic viscosity
3. Fire point
4. Density

4.6. Apparatus Used For Evaluation of Fuel Properties

The following equipments were employed for the estimation of the properties of the water-diesel emulsion.

4.6.1 Bomb Calorimeter

The wisdom scientific works make isothermal bomb calorimeter was used to compute the gross heat of combustion of an emulsion fuel sample. A one-gram fuel sample was burnt out completely with the help of pure oxygen in the bomb of the calorimeter. The fuel sample was ignited by creating a spark in bomb with the help of electrically. Burning of emulsion fuel liberates heat in the bomb of the calorimeter. Due to heat transfer from the bomb, temperature of water surrounding the bomb starts increasing. This increase in temperature was recorded. The water equivalent was also evaluated with the aid of dry and pure benzoic acid as an analysis fuel. The expression used for calculating the gross calorific value of emulsified fuel is given below:

$$HCV = \frac{W_c \times \Delta T}{M_s} + (E_1 + E_2) \quad (4.2)$$

Here HCV represents the higher calorific value of the fuel. Whereas, W_c and ΔT represents the water equivalent for calorimeter (Cal/°C) and increase in temperature of water (°C), respectively. M_s , E_1 and E_2 represent the weight of fuel sample, micro wire and cotton thread, respectively. Pictorial view is shown in figure 4.10.



Figure 4.10: Pictorial view of bomb calorimeter

4.6.2 Pensky Martin (Closed Cup) Apparatus

The flash point is a lowest temperature at which, on introducing the test flame into the oil cup a distinct flash was observed whereas, the fire point is a temperature at which the sample of oil starts to fire continuously for minimum 5 seconds. The fire point of the water-diesel emulsion was evaluated as per IS: 1448. The oil cup was filled up to mark with fuel sample. Fuel sample was stirred at a constant rate (approximately 60 RPM) to maintain uniform temperature distribution throughout the sample. The oil cup was heated in such a way that its temperature increases by 5 to 6 C per minute. The thermometer having range -10 to 400 °C was used to measure temperature in oil cup. After every 1 °C rise in temperature, shutter was used to introduce flame. Pictorial view is shown in figure 4.11.



Figure 4.11: Pictorial view of pensky martin (closed cup) apparatus

4.6.3 The Brookfield Viscometer

Brookfield Viscometer was used to determine the viscosity of fuel samples. The equipment consists of a water jacket, adaptor, spindle and a cylindrical sample holder. The CPE-42 spindle is used. The sample of fuel was put into the sample holder and immersed spindle of the viscometer run into the sample holder. Then spindle determine the drag when it rotates into the sample holder. The capacity of the sample holder is 1 ml and temperature of the sample was measured by the temperature sensor. Pictorial view is shown in figure 4.12.



Figure 4.12: Pictorial view of brookfield viscometer

4.7. Evaluation of Engine Performance Characteristics of Emulsion Fuel

A 4-stroke, single cylinder, variable compression ratio CI engine was utilized for evaluating the performance characteristics. All the blends of emulsion fuel were tested on a variable compression ignition diesel engine to analyze its behaviour at five different loads (0, 2, 4, 6, 8) and three different compression ratios (14, 16 and 18). The tilting cylinder block mechanism was used to change compression ratio without stopping the engine.

4.7.1. Test Setup Used For Experimental Work

The arrangement for measurement of airflow, fuel flow, temperature and load was provided. Air box, fuel tank, manometer, transmitters for air, fuel measuring unit and fuel flow measurements, engine indicator and process indicator has been assembled separately in the panel box. Rotameter was used to control the flow of water through calorimeter and interconnected water jackets around cylinder block and head. Load cell sensor was used to vary the load on an eddy current dynamometer that is coupled to the engine. Labview based Engine Performance Analysis software package "Enginesoft" was provided for online performance evaluation. Figure 4.13 shows the pictorial view of variable compression ratios engine setup. Whereas, schematic view of the experimental setup is shown in figure 4.14. The engine specifications are listed in table 4.3.

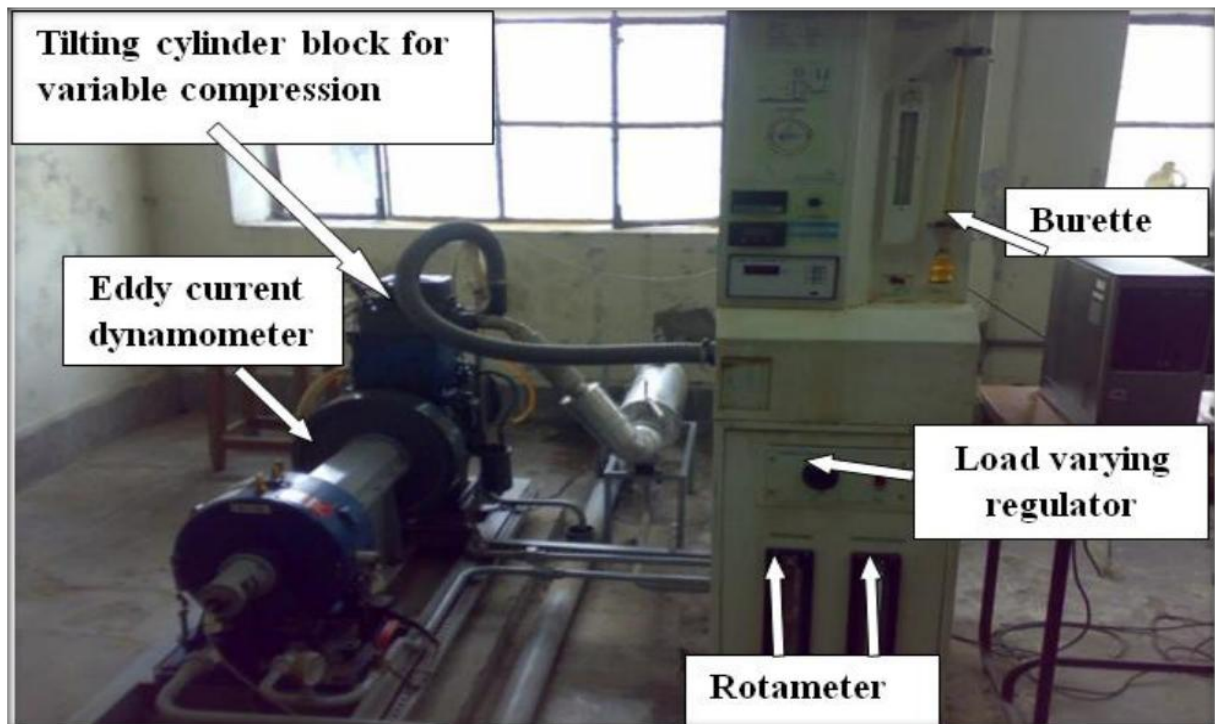


Figure 4.13: Single cylinder, 4-stroke, VCR engine

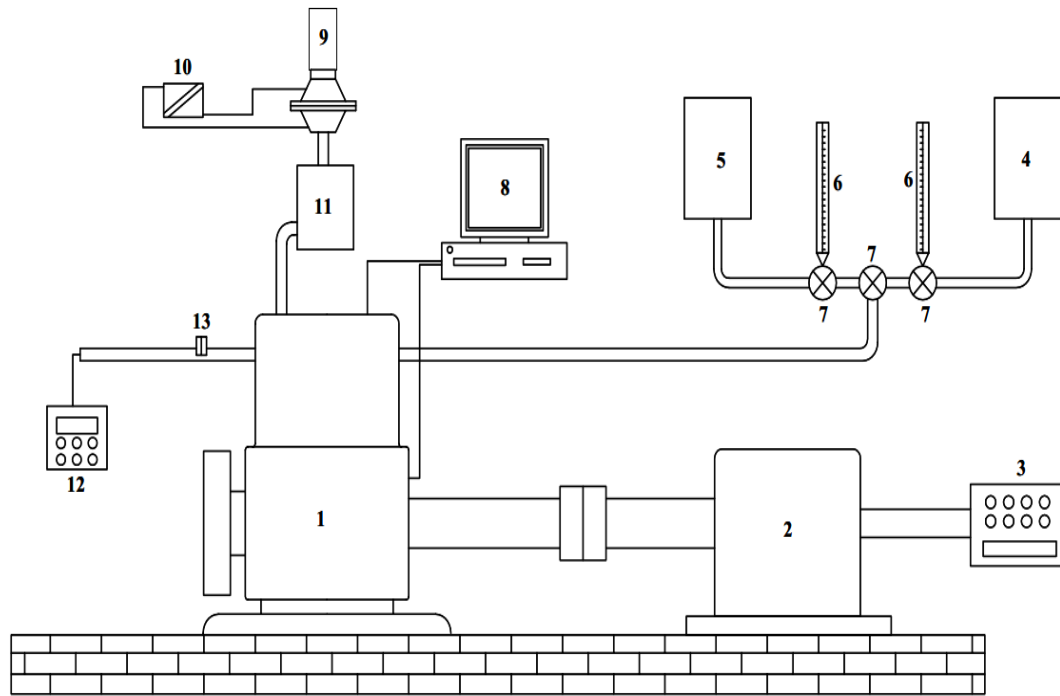


Figure 4.14: Schematic diagram of experimental setup.

- | | | |
|-------------------------------------|-------------------------|---------------------------|
| (1) VCR Diesel Engine | (2) Alternator | (3) Loading Device |
| (4) Emulsion Tank | (5) Diesel Tank | (6) Burette |
| (7) Fuel Control Valve | (8) Data Control System | (9) Air Filter |
| (10) Manometer | (11) Surge Tank | (12) Exhaust Gas Analyser |
| (13) Exhaust Gas Temperature Sensor | | |

Table 4.3: Engine Specifications

Engine Type	Single Cylinder, 4-Stroke, Water Cooled, VCR Engine
Make Type	Kirloskar
Bore	87.5 mm
Stroke	110 mm
Length of Connecting Rod	234 mm
Rated Power	3.75 kW @ 1500 RPM
Compression Ratio	Range from 12-18
Orifice diameter	20 mm
Dynamometer arm length	145 mm
Cooling media	Water cooled
Load indicator	Range 0-50 Kgf, Digital
Load sensor	Strain gauge, range 0-50 Kgf

Loading device	Eddy current dynamometer
Rotameter	Engine cooling 40-400 LPH; Calorimeter 25-250 LPH
Temperature sensor	Thermocouple, Type K
Speed indicator	Digital with non contact type speed sensor

4.7.2. Performance Parameters Evaluated

Performance parameters evaluated for comparing all the prepared fuel blends are

1. Brake Power
2. Brake thermal efficiency
3. Fuel consumption
4. Brake specific fuel consumption

4.7.3. Experimental Procedure

The following experimental procedure was followed during the experiment:-

1. Fill the diesel in the fuel tank.
2. In the starting, adjust the CR of the engine to 14:1.
3. After starting the water supply, adjust the flow rate of cooling water at 80 LPH and for engine at 300 LPH and make sure the proper supply of water to piezo sensor for cooling and dynamometer cooling.
4. Check all the connections before giving electric supply to the computer.
5. Click on the lab view based "**Enginesoft**" software package for on screen evaluation of performance.
6. Run the engine.
7. Set the value of specific gravity and heating value of the fuel in the software. Then select the run option and run the engine for 15 minutes without any load.
8. Select log option in the software and assign the fuel supply by revolving the supply knob. Before turning on the fuel supply knob, check that gas analyzer is available there.
9. After 1 minute, the display changes to input mode, then enter the values of water flows in calorimeter and cooling jacket. Now enter the name of the file in the software and insert the probe of gas analyzer into the exhaust at appropriate place. Then it let for few minutes so that it could stabilize.
10. Save the reading for no load condition.

11. Repeat the experiment at different load and CR.
12. Save the readings.
13. After the completion of the experiment, remove the load from the engine and turn off the engine.
14. Shut down the computer.
15. After a few minutes, turn off the water supply.

4.8. Evaluation of Engine Emission

The Maxicem 9000 gas analyser (provided by **Ace Gas Analysers Pvt. Ltd**) was used to measure common pollutants from compression ignition engine. Exhaust parameters measured for comparing all the prepared fuel blends are CO, CO₂, HC and NO.

4.8.1. Equipment Used In the Evaluation of Engine Emissions

The Maxicem 9000 is a portable gas analyser, designed to operate from 7.2/600 mAH volt Ni-Mh rechargeable batteries. The unit can measure O₂, CO, CO₂, SO₂, NO, excess air derived and combustion efficiency. The other parameters that it can measure are temperature at the tip of sampling probe and ambient temperature.

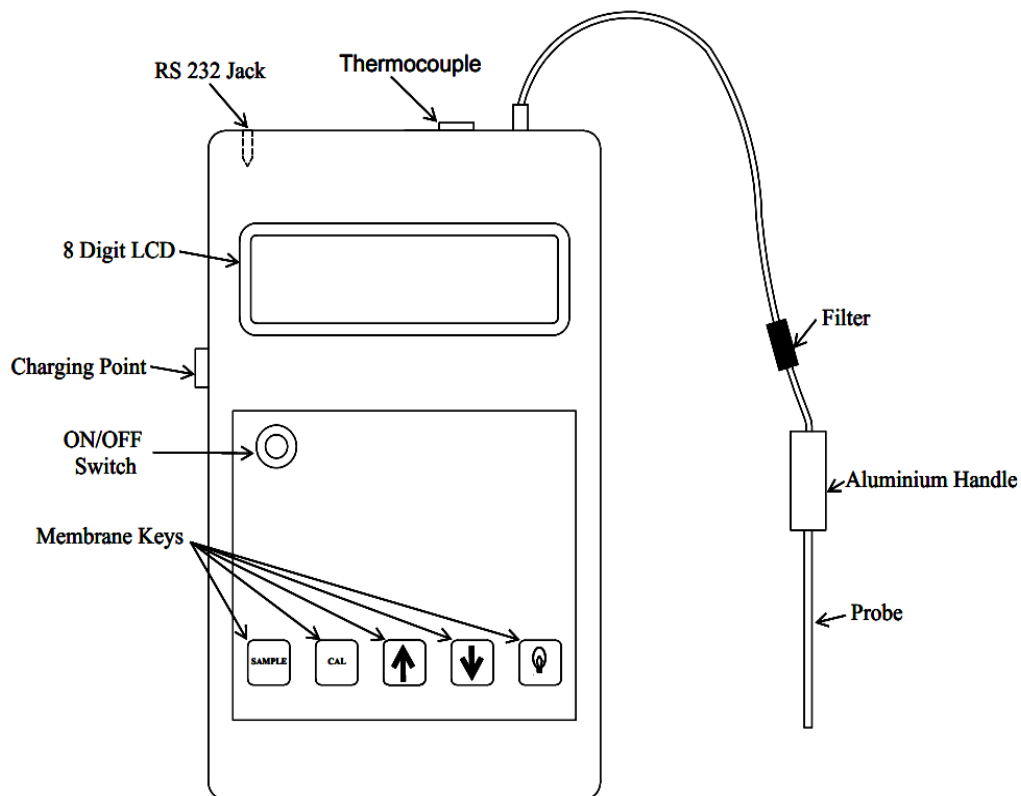


Figure 4.15: ACE gas analyser

It has the capacity to store the reading in its internal memory to recall them later. It can store maximum 60 readings. The filter is provided to take care of particulate matter and moisture, which enables it to work in harsh working condition. A powerful diaphragm pump is employed to draw sample from the stack. Specifications of ACE Maxicem 9000 are given in below.

Table 4.4: Specification of ACE Maxicem 9000

SR.	Parameters	Range	Accuracy	Resolution
1	O ₂	0 to 21 %	±2 % of reading	0.1 %
	CO	0 to 5000 ppm	±5 % of reading	1 ppm
2	Type CRAL Thermocouple	0 to 600 C	±3 % of reading	1°C
	CO ₂ Derived	0 to 21 %	±5 % of reading	
	Combustion Efficiency derived	0 to 100 %	±1 % between 70 % and 95 %	0.1 %
	Excess air derived	0 to 850 %	1 %	
	SO ₂	0 to 5000 ppm	±5 %	1 ppm
	NO _x	0 to 5000 ppm	±5 %	1 ppm
3	Power	7.2 V/600 MAH Ni-Mh rechargeable battery with charger		
4	Battery	Capacity typical 3 hours		
5	Probe	Suitable 0 to 600°C temperature 30 cm rigid section with taper plug 4 meter neoprene tubing		
6	Display	8 character Dot matrix LCD		
7	Switch	Membrane polycarbonate keyboard		

4.8.2. Procedure to Take Readings

The following procedure was followed while taking the readings:-

1. Press 'sample' key.
2. Press 'sample' key again to select desired fuel (example diesel, kerosene etc) with the help of ↑ key and ↓ key.
3. Press 'sample' key again, the display will show 'insert probe'. At this moment, insert probe into the engine exhaust.
4. After inserting probe, press 'sample' key again, the display will show 'Warm-up'.

5. After 20 seconds, the pump will start and the display will show 'sampling'.
6. After 40 seconds, all the parameters will be shown on the display.
7. Press ↑ key twice to save the reading.

After performing the experimental work on the VCR diesel engine, data obtained from all the blends of emulsion fuel (with and without TiO₂) were used to compare the performance and emission characteristics with the characteristics of diesel.

Chapter 5

Results and Discussions

This chapter discusses results with the help of graphs and reasons behind them. The experiments are conducted on constant speed, VCR diesel engine to study the behaviour/impact of water-diesel emulsion (with and without titanium oxide nanoparticles) on the performance and emission characteristics. In addition to performance and emission characteristics, various properties of prepared fuel are compared with diesel fuel. The experimental results are divided into three parts:

1. Comparison of water-diesel emulsion, titanium oxide nanoparticle blended water-diesel emulsion and diesel on the basis of various fuel properties like viscosity and calorific value.
2. Comparative analysis of all the above-mentioned fuels on the basis of their performance characteristics.
3. In the last their emission characteristics are discussed.

5.1. Comparison of Fuel Properties

All the prepared fuel blends are compared with diesel on the basis of viscosity and calorific value.

5.1.1. Calorific Value

The variation in the calorific value of water-diesel emulsion with 10 % and 15 % water content with the addition of the titanium oxide nanoparticle is shown in figure 5.1. The lowest calorific value is observed with E15. This is due to the replacement of 15 % diesel by water in E15. Further, the improvement in calorific value of both E10 and E15 is observed with the addition of titanium oxide nanoparticles. Nearly 3.1 % and 6.7 % improvement in calorific value of E15 is obtained with the addition of 50 ppm and 70 ppm titanium oxide nanoparticles, respectively. Whereas, 2.7 % and 4.7 % increase in calorific value of E10 is observed with the addition of 50 ppm and 70 ppm nanoparticles.

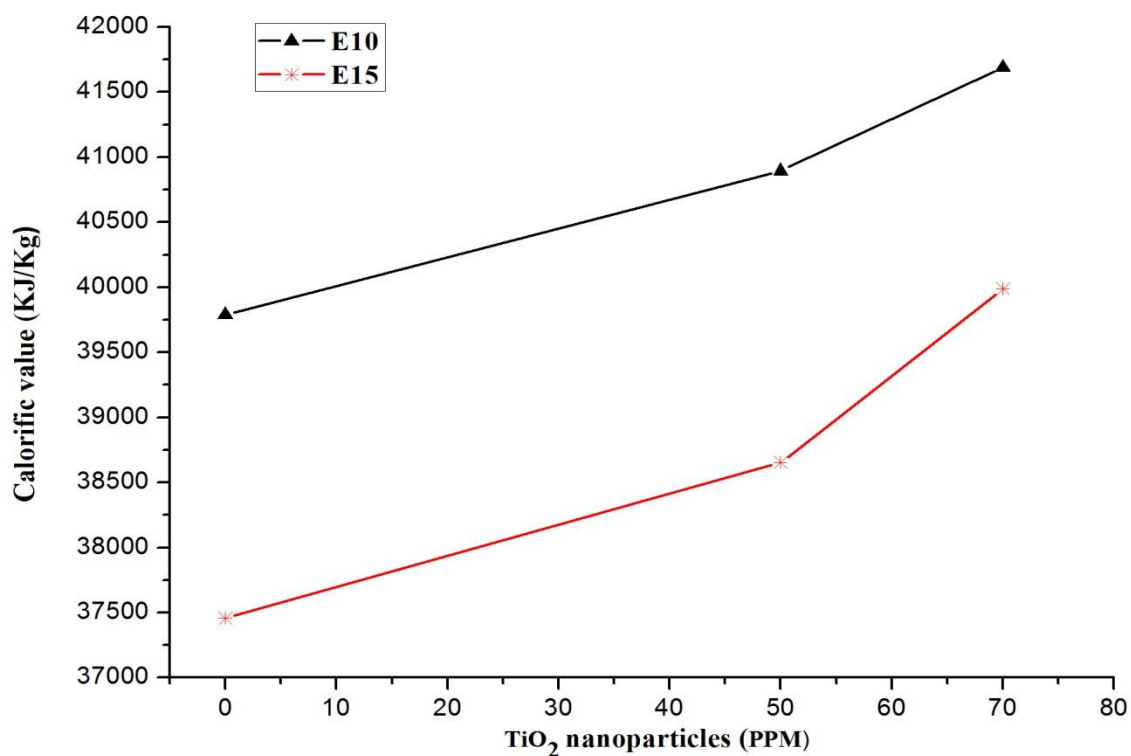


Figure 5.1: Variation in calorific value with the addition of TiO₂ nanoparticles.

5.1.2. Viscosity

The effect of titanium oxide nanoparticles on the viscosity of water-diesel emulsion with 10% water is shown in figure 5.2. The increase in viscosity of E10 is observed with the addition of titanium oxide nanoparticles. Nearly, 1.4 % and 2.4 % increase in viscosity is observed with the addition of 50 ppm and 70 ppm titanium oxide nanoparticles, respectively. Whereas, 1.2 % and 2 % increase in viscosity is observed in the case of E15. This increase in viscosity is due to the enhancement in resistance between the layers of fluid with the addition of titanium

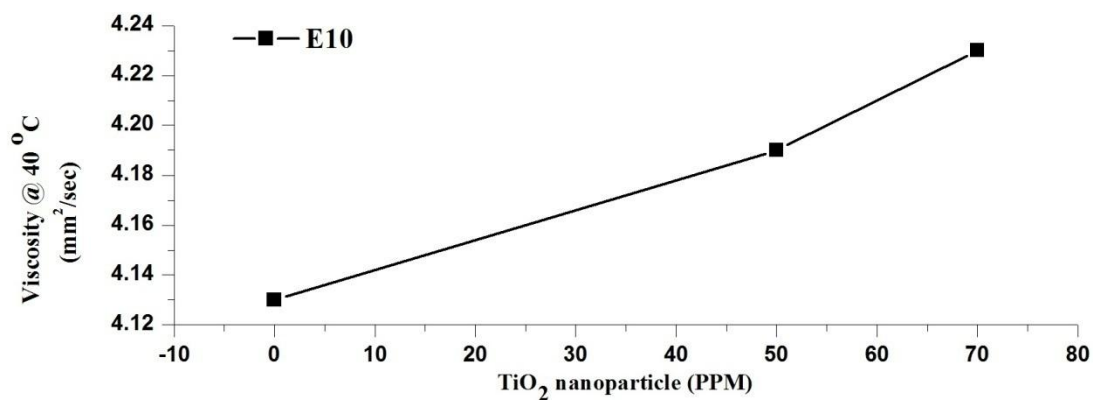


Figure 5.2: Variation in viscosity of E10 with the addition of TiO₂ nanoparticles.

oxide nanoparticles. Optimum viscosity is desired because higher viscosity of fuel leads to poor atomization of fuel inside the combustion chamber. Further, more power is required to pump fuel of higher viscosity. On the other hand, lower viscosity results in leakage problem. Therefore, optimum viscosity should be compromised between both the limits. The effect of titanium oxide nanoparticles on E15 is shown in figure 5.3.

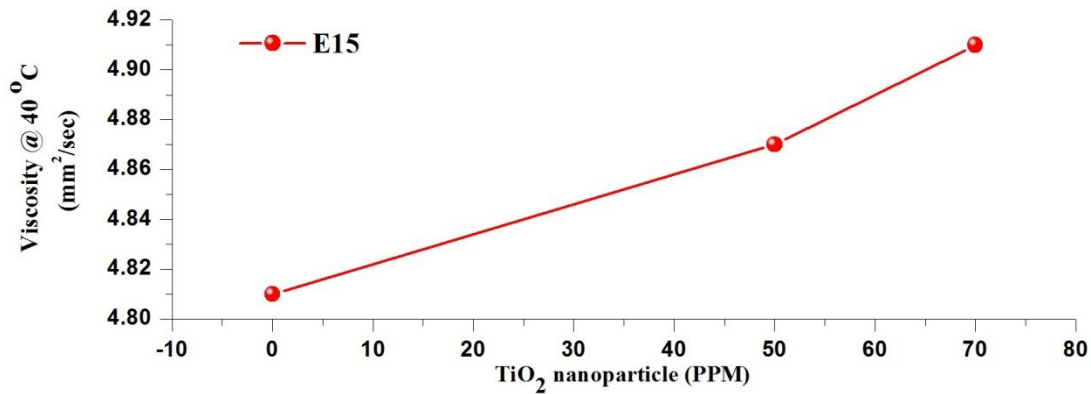


Figure 5.3: Variation in viscosity of E15 with the addition of TiO₂ nanoparticles.

5.2. Comparison of Performance Characteristics

5.2.1 Brake Power (BP)

- **Effect of blends and load on brake power**

The experiment on the VCR diesel engine was conducted with diesel and six blends of water-diesel emulsion (E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50, E15TiO₂70) at compression ratio 14, 16 and 18. During the experiment, the load on the engine was varied from 0 to 8 kg with 2 kg step size. The variation of brake power with respect to load at different CR are shown in figure 5.4, 5.5 and 5.6. From the above-mentioned figures, it is apparent that brake power increases with the increase in load on the engine due to the consumption of more fuel [1]. It is observed that at low load conditions, the brake power for pure diesel and water-diesel E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50 and E15TiO₂70 is almost same. At higher loads, marginal difference is detected for the all fuels, but this difference is insignificant. This is mainly due to complete combustion takes place inside the combustion chamber due to the micro-explosion phenomenon of water-diesel emulsion. A slight drop in the brake power is observed with E15. This is due to lower calorific value of E15 that is nearly 16% lower than the calorific value of pure diesel. Addition of titanium oxide nanoparticles to water-diesel emulsion shows slight rise in brake power at higher load due to

secondary atomization of nanofluids. At higher loads, E10TiO₂70 shows maximum brake power.

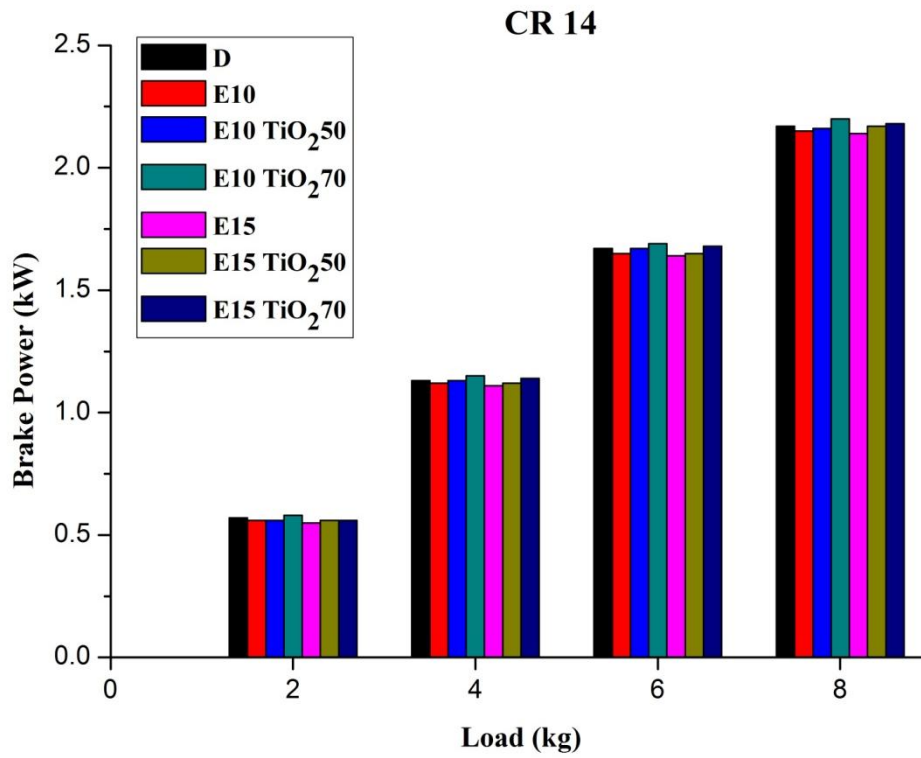


Figure 5.4: Variation of bp with respect to load at CR 14.

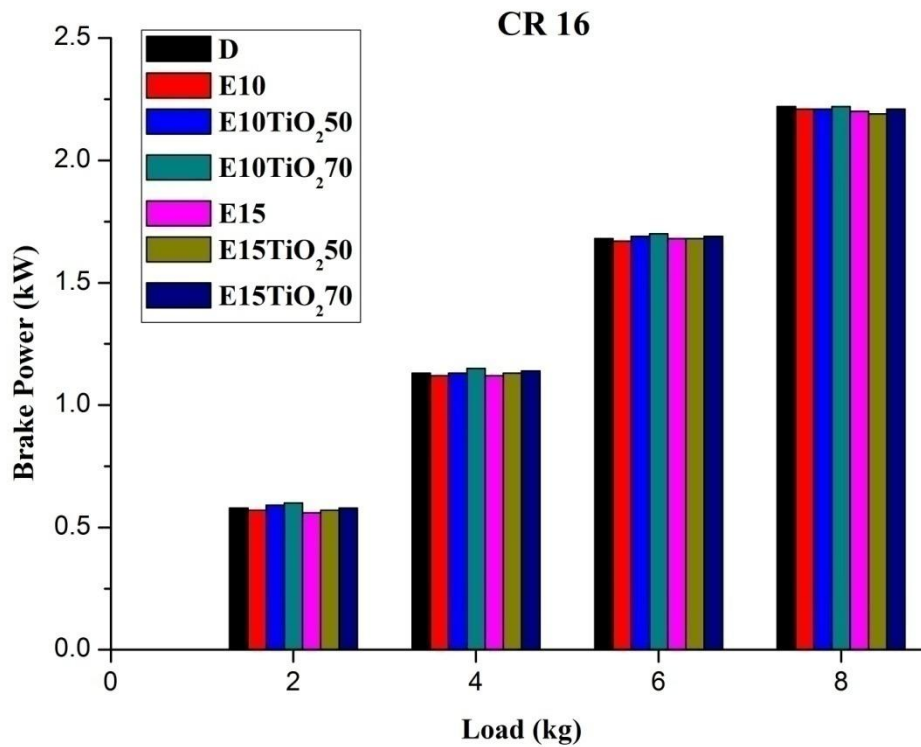


Figure 5.5: Variation of bp with respect to load at CR 16.

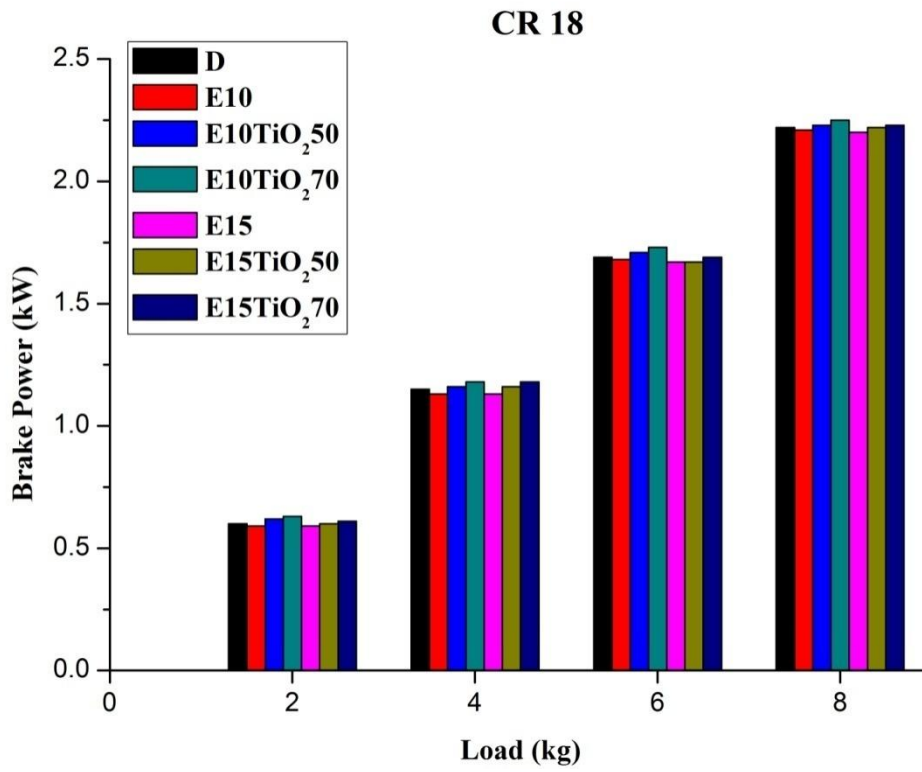


Figure 5.6: Variation of bp with respect to load at CR 18.

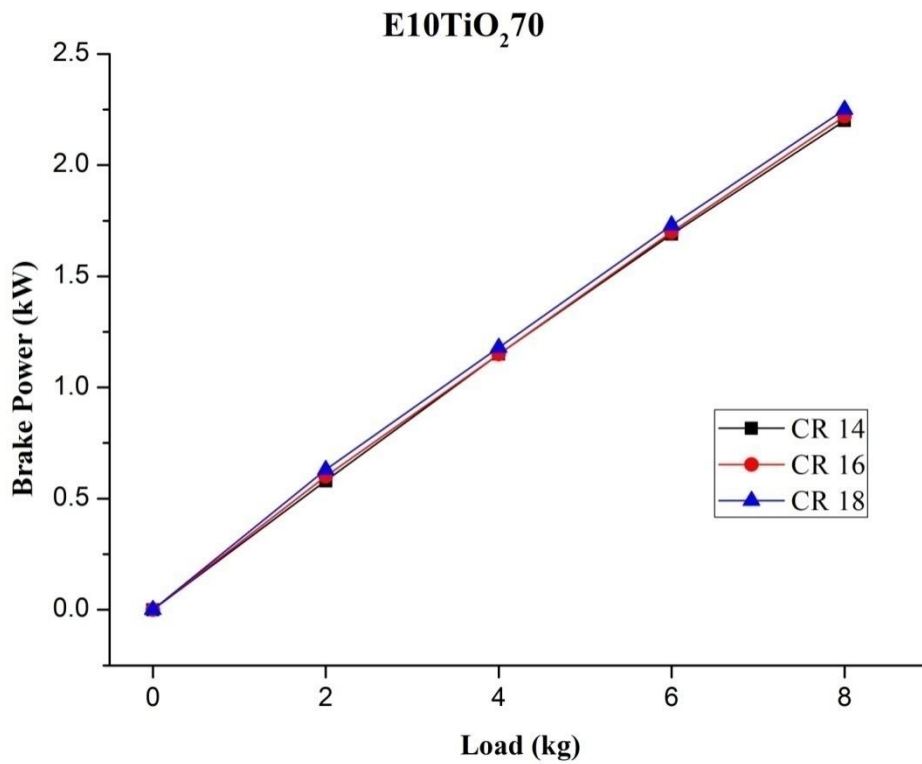


Figure 5.7: Variation of bp with respect to load for E10TiO₂ 70 at CR 14, 16 and 18.

- **Effect of Compression Ratio on Brake Power**

Variation of brake power with respect to compression ratio (14, 16 and 18) for E10TiO₂70 is shown in figure 5.7. Maximum brake power is observed with E10TiO₂70 at compression ratio 18. A slight rise in brake power is observed with the increase in compression ratio [1]. This can be due to better atomization as a result of a higher temperature and pressure of air, micro-explosion phenomenon of water-diesel emulsion and secondary atomization of nanofluids. The effect of compression ratio on all fuels is shown in table 5.1.

Table 5.1: Brake power (kW) at CR 14, 16 and 18 corresponding to full load.

CR	D	E10	E10TiO ₂ 50	E10TiO ₂ 70	E15	E15TiO ₂ 50	E15TiO ₂ 70
14	2.17	2.15	2.16	2.20	2.14	2.17	2.18
16	2.22	2.21	2.21	2.22	2.2	2.19	2.21
18	2.22	2.21	2.23	2.25	2.2	2.22	2.23

5.2.2 Brake thermal efficiency

- **Effect of blends and load on Brake thermal efficiency**

The brake thermal efficiency of diesel, E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50 and E15TiO₂70 at varying load and a compression ratio (14, 16 and 18) is demonstrated in figure 5.8, 5.8 and 5.9. The load on the engine was varied from 0 to 8 kg. Rise in brake thermal efficiency is observed with increase in load for all the prepared fuels and diesel. It is also observed that the brake thermal efficiency of E15 is lesser than E10 due to lower calorific value, lower volatility, higher density, higher viscosity and higher fuel consumption. Improvement in brake thermal efficiency is observed for both water-diesel emulsions (E10 and E15) and titanium oxide nanoparticle blended water-diesel emulsions (E10TiO₂50, E10TiO₂70, E15TiO₂50 and E15TiO₂70) as compared to diesel. Further, it is noted that brake thermal efficiency also increases with the dosing level of a titanium oxide nanoparticle in both E10 and E15. Among all the prepared fuels E10TiO₂70 shows maximum brake thermal efficiency at full load and compression ratio 18 which is nearly 3.89 % higher than diesel. This can be due to secondary atomization of titanium oxide nanoparticle encapsulated water molecule immediately after the primary micro explosion phenomenon of water-diesel emulsion. Further, the presence of nanoparticle in fuel helps in complete combustion due to higher evaporation rates, shorter physical ignition delay, prolonged flame sustenance and higher calorific value.

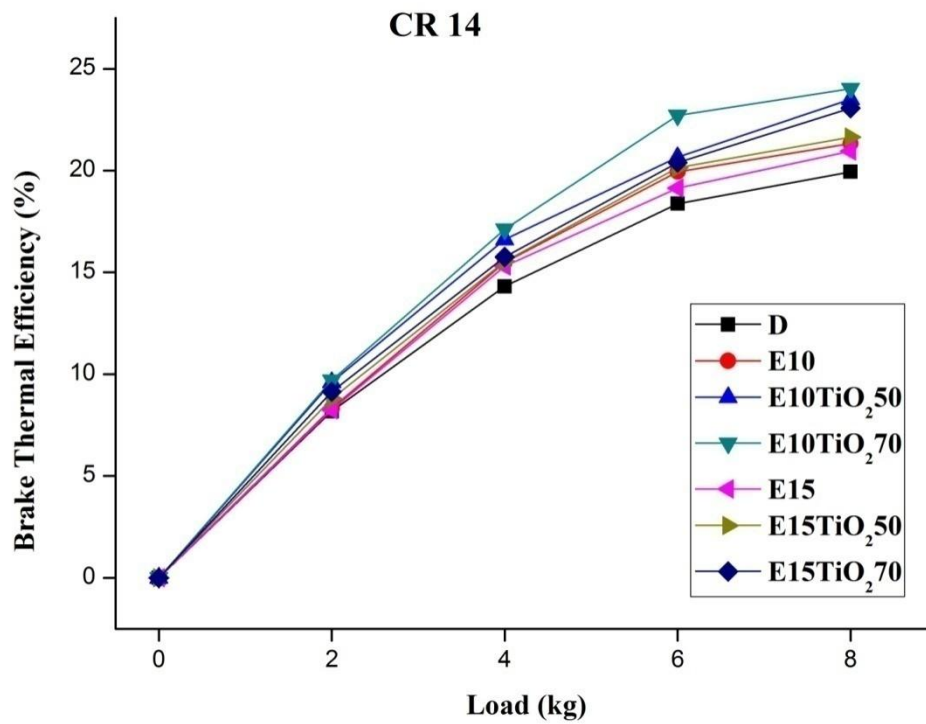


Figure 5.8: Variation of BTE with respect to load at CR 14.

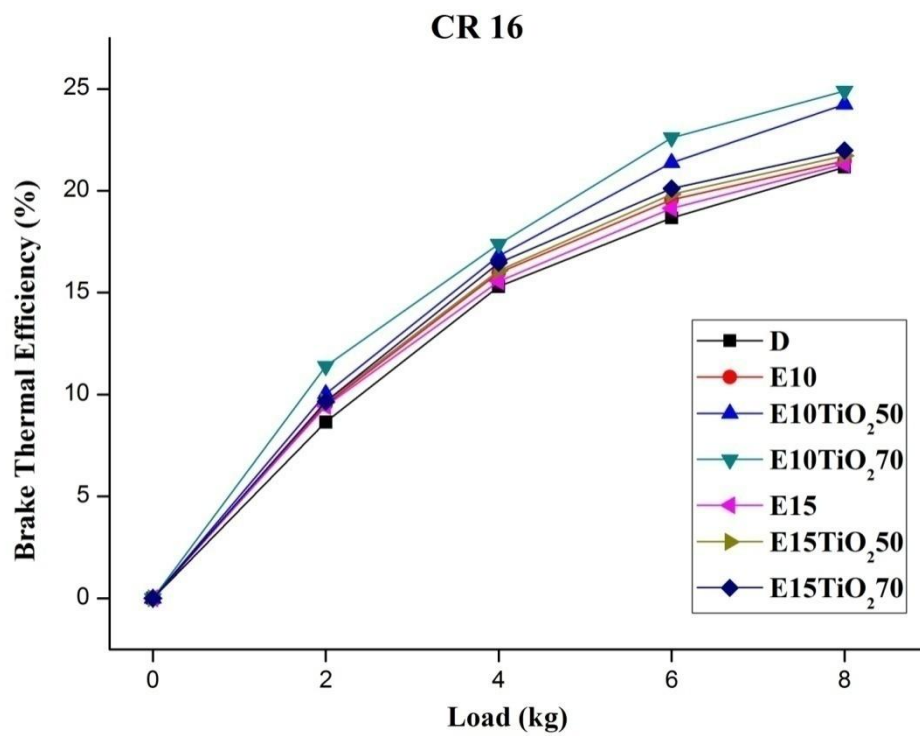


Figure 5.9: Variation of BTE with respect to load at CR 16.

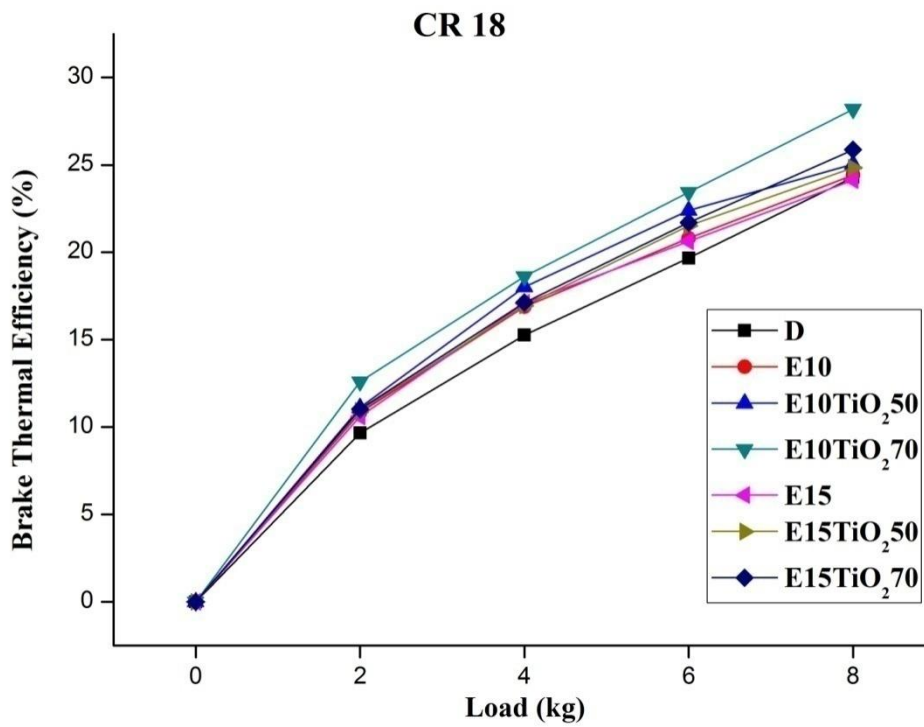


Figure 5.10: Variation of BTE with respect to load at CR 18.

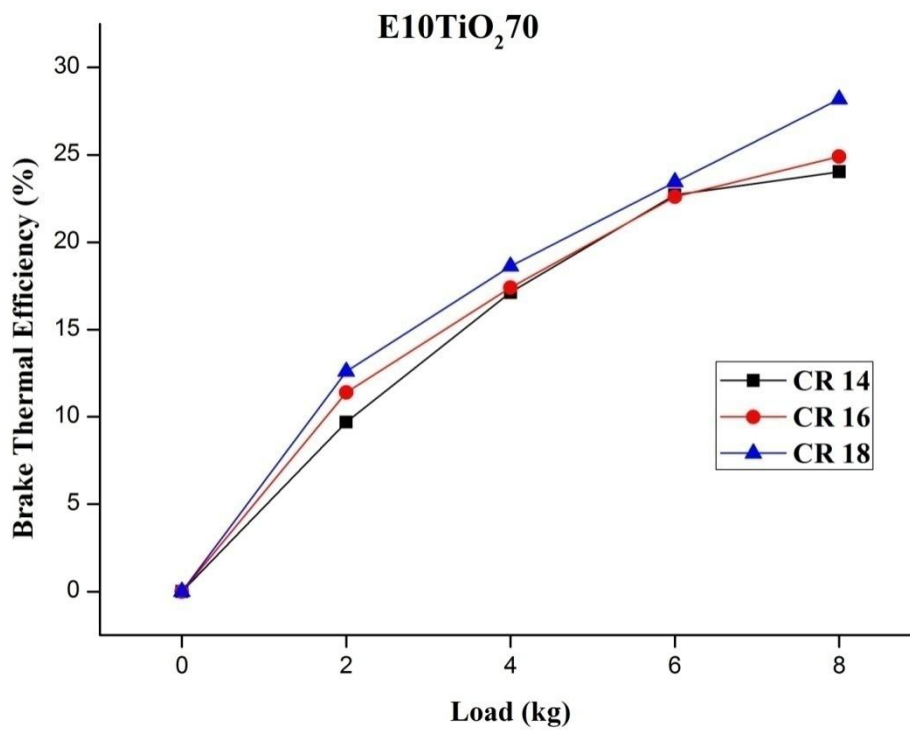


Figure 5.11: BTE variation for E10TiO₂70 at CR 14, 16 and 18.

- **Effect of compression ratio on BTE**

Figure 5.11 demonstrates the increasing trend for brake thermal efficiency with respect to load at all CR and the maximum brake thermal efficiency is obtained with E10TiO₂70 at CR 18 corresponding to full load. E10TiO₂70 at compression ratio 18 shows 3.29 % and 4.16 % higher brake thermal efficiency as compared to compression ratio 16 and 14, respectively. Higher brake thermal efficiency at compression ratio 18 can be due to shorter ignition delay and proper combustion of fuel because of higher temperature of air after compression stroke [2]. The variation of brake thermal efficiency with respect to compression ratio at full load is shown in table 5.2.

Table 5.2: Brake thermal efficiency (%) at CR 14, 16 and 18 corresponding to full load.

CR	D	E10	E10TiO ₂ 50	E10TiO ₂ 70	E15	E15TiO ₂ 50	E15TiO ₂ 70
14	19.94	21.33	23.50	24.03	20.96	21.64	23.07
16	21.16	21.47	24.25	24.90	21.31	21.73	21.97
18	24.30	24.43	25.05	28.19	24.12	24.84	25.87

5.2.3 Fuel Consumption

- **Effect of blend and load on fuel consumption**

The experiment was conducted with diesel and six blends of water-diesel emulsion fuel (E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50, E15TiO₂70) at compression ratio 14, 16, 18. The load on the engine was varied from 0 to 8 kg. From figures 5.12, 5.13 and 5.14, it is apparent that fuel consumption for diesel and water-diesel emulsion blends increases with the increase in load on the engine. It is observed that E10 and E15 show higher fuel consumption as compared to conventional diesel and titanium oxide nanoparticle blended water diesel emulsions [3]. This can be due to lower heating value and higher viscosity of water diesel emulsions as compared to diesel. The titanium oxide nanoparticle blended water-diesel emulsion shows lower fuel consumption as compare to water-diesel emulsion without nanoparticles. This reduction in fuel consumption can be due to increase in calorific value with the addition of the titanium oxide nanoparticle. Further, the nanoparticles in fuel, eliminate the problem of carbon deposits in the cylinder that leads to decrease in friction power, which results in the reduction of fuel consumption. E10TiO₂70 shows minimum fuel consumption at all loads and compression ratios.

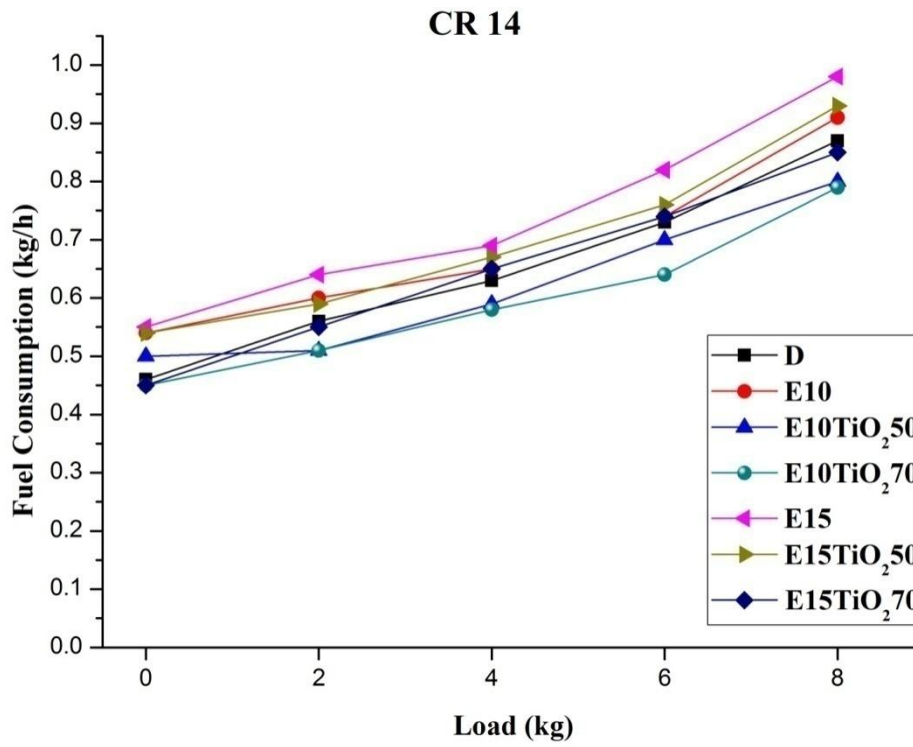


Figure 5.12: Variation of FC with respect to load at CR 14.

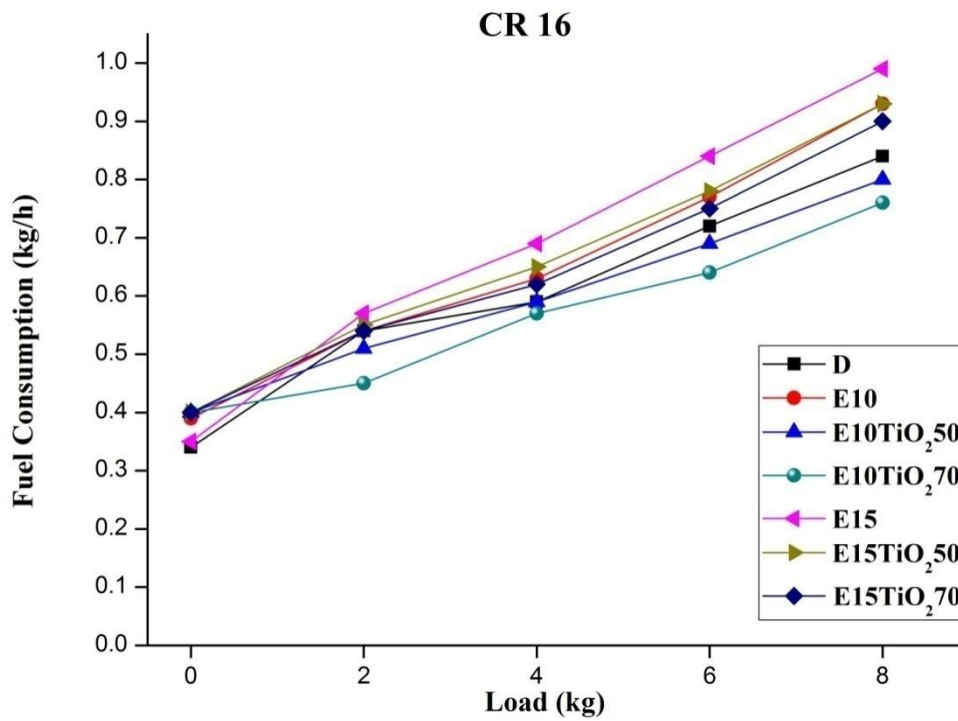


Figure 5.13: Variation of FC with respect to load at CR 16.

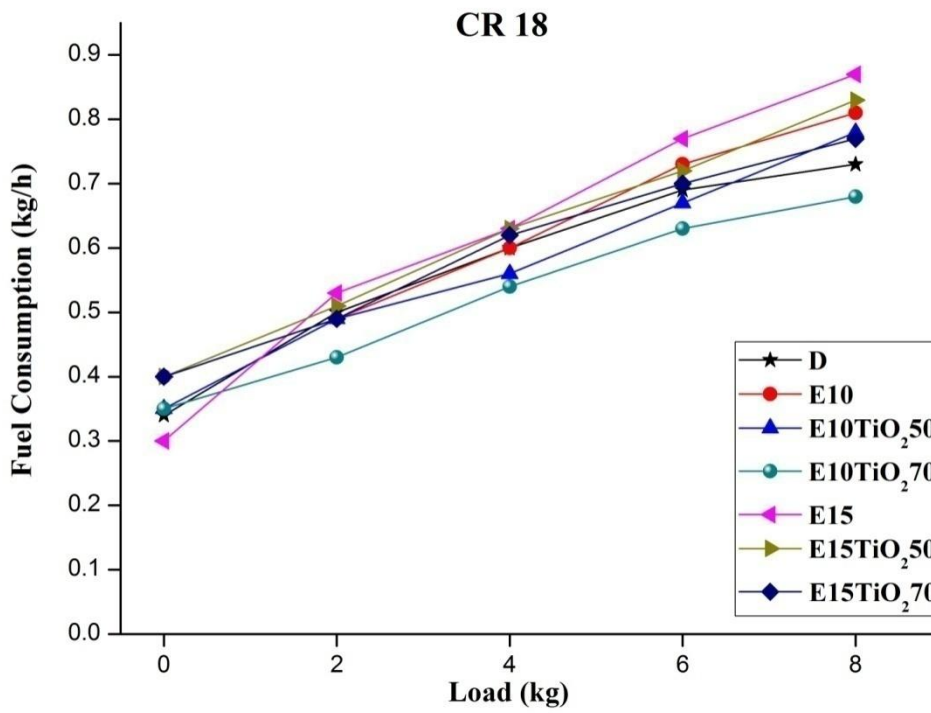


Figure 5.14: Variation of FC with respect to load at CR 18.

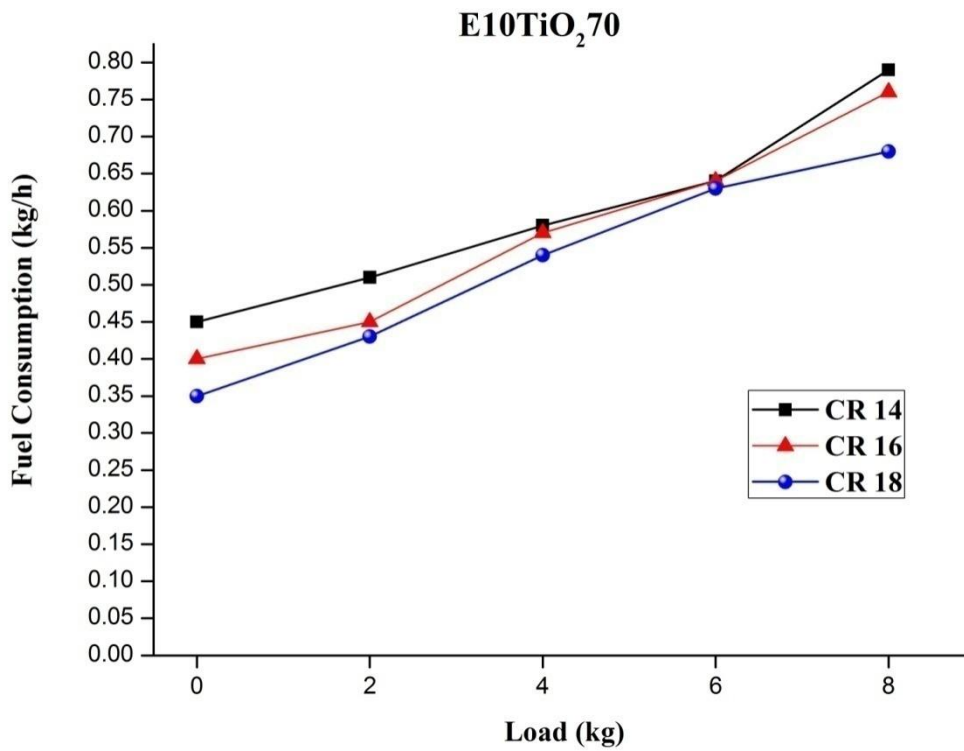


Figure 5.15: FC variation for E10TiO₂70 at CR 14, 16 and 18.

- **Effect of CR on fuel consumption**

Effect of compression ratio on fuel consumption is shown in figure 5.15. Minimum fuel consumption is observed at compression ratio 18. An increase in fuel consumption is found with the decrease in compression ratio. The marginal rise in fuel consumption can be due to poor atomization of fuel at lower compression ratios. The fuel blend E10TiO₂70 shows least fuel consumption at compression ratio 18. The variation of fuel consumption for all the fuels with respect to compression ratio at full load is shown in table 5.3.

Table 5.3: Fuel consumption (kg/h) at CR 14, 16 and 18 corresponding to full load.

CR	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
14	0.87	0.91	0.8	0.79	0.98	0.93	0.85
16	0.84	0.93	0.8	0.76	0.99	0.93	0.9
18	0.73	0.81	0.78	0.68	0.87	0.83	0.77

5.2.4. Brake Specific Fuel Consumption (BSFC)

- **Effect of blends and load on BSFC**

The variation of brake specific fuel consumption for diesel and different blends of emulsified fuel at different loads is reported in figure 5.16, 5.17 and 5.18. The experiment was performed with diesel and six blends of water-diesel emulsion fuel (E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50, E15TiO₂70) at three different compression ratios (14, 16 and 18). Decrease in brake specific fuel consumption is noticed with the rise in load on engine for all the fuels. Among all the prepared fuels, E15 shows maximum brake specific fuel consumption at all compression ratios. This can be due to higher fuel consumption and lower calorific value of E15 [1, 3, 4]. Improvement in brake specific fuel consumption is observed with the addition of nanoparticles. The lowest brake specific fuel consumption is observed with E10TiO₂70. This can be due to the presence of titanium oxide nanoparticles in water-diesel emulsion [5].

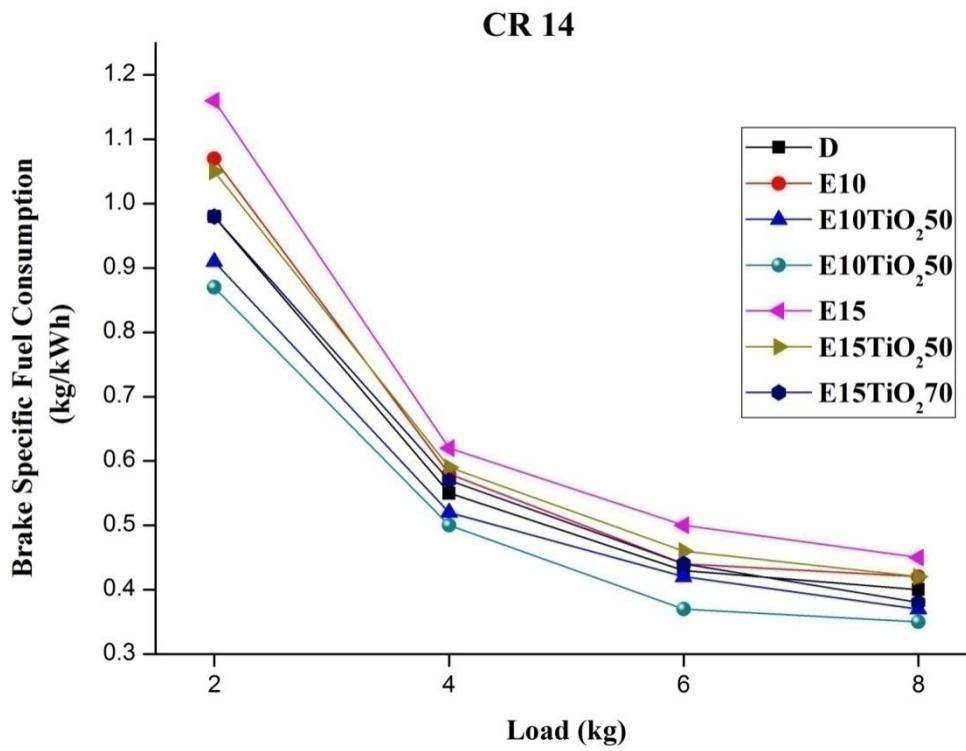


Figure 5.16: Variation of BSFC with respect to load at CR 14.

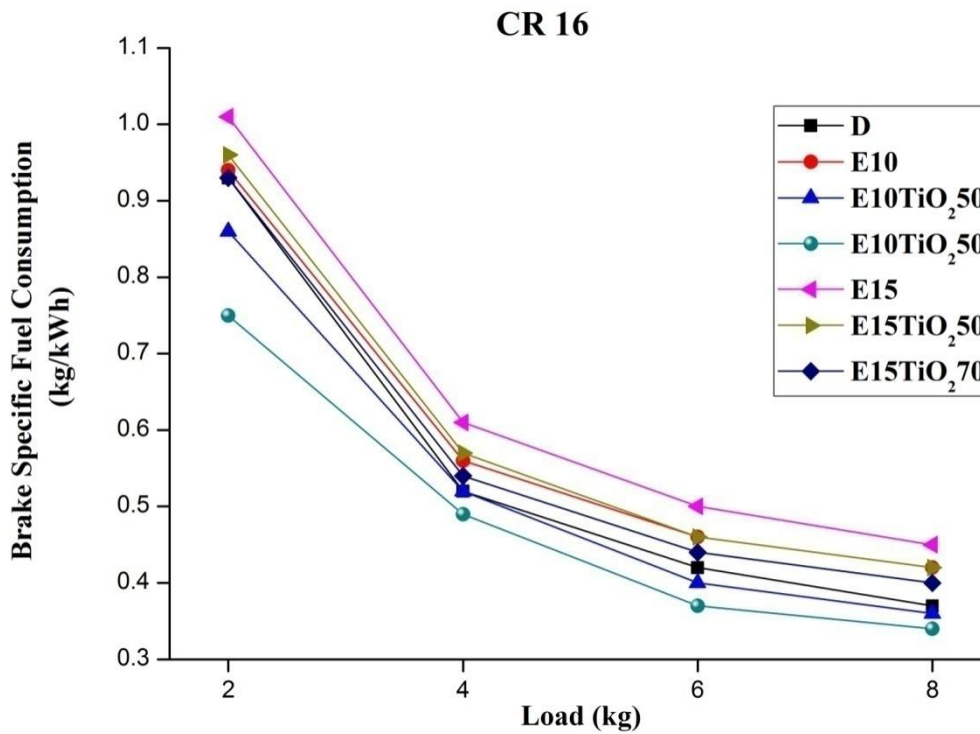


Figure 5.17: Variation of BSFC with respect to load at CR 16.

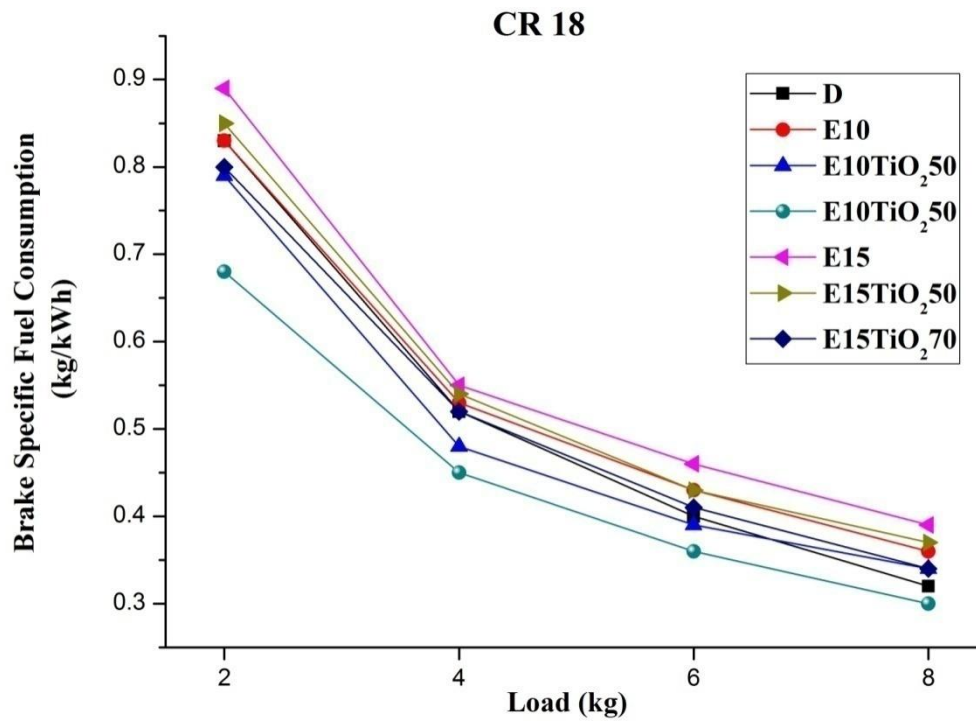


Figure 5.18: Variation of BSFC with respect to load at CR 18.

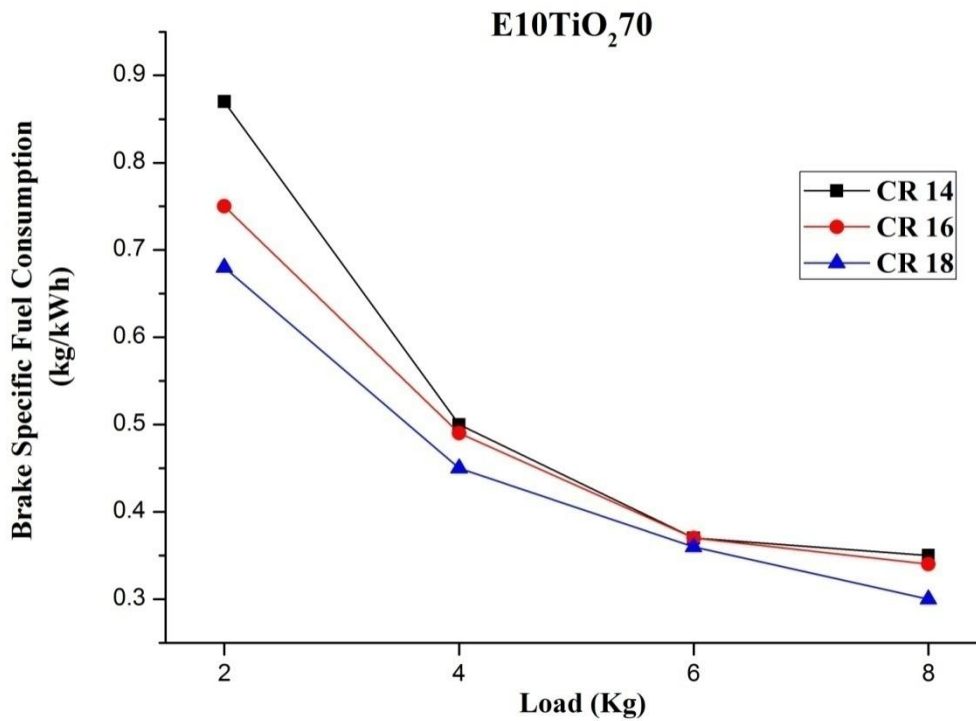


Figure 5.19: BSFC variation for E10TiO₂70 at CR 14, 16 and 18.

- **Effect of compression ratio on BSFC**

The brake specific fuel consumption is found to be decreased with the increase in compression ratio from 14 to 16. The brake specific fuel consumption corresponding to compression ratio 18 is found lower than brake specific fuel consumption at compression ratio 14 and 16. This improvement in brake specific fuel consumption with the increase in compression ratio is due better atomization fuel in the combustion chamber which results in the improvement of fuel combustion [1]. The variation of brake specific fuel consumption for E10TiO₂70 with respect to load at compression ratio 14, 16 and 18 is shown in figure 5.19. The variation of brake specific fuel consumption for all the fuels with respect to compression ratio at full load is shown in table 5.4.

Table 5.4: BSFC (kg/kWh) at CR 14, 16 and 18 corresponding to full load.

CR	D	E10	E10TiO ₂ 50	E10TiO ₂ 70	E15	E15TiO ₂ 50	E15TiO ₂ 70
14	0.4	0.42	0.37	0.35	0.45	0.42	0.38
16	0.37	0.42	0.36	0.34	0.45	0.42	0.4
18	0.32	0.36	0.34	0.3	0.39	0.37	0.34

5.3. Comparison of Emission Characteristics

5.3.3. Nitrogen Oxide (NO_x) emission

- **Variation of NO_x with respect to load**

The main reason behind the formation of NO_x emission from compression ignition engine is dissociation of gases at high temperature. The variation of NO_x emission with respect to load at compression ratios 14 for pure diesel, E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50 and E15TiO₂70 is shown in figure 5.20. Whereas, the variation at compression 16 and 18 are shown in figure 5.21 and 5.2, respectively. It is found that the water-diesel emulsion with 15% water content produce the least amount of NO_x emission as compared to other fuels [3]. Reason behind this reduction is the decrease in peak cycle temperature due to the vaporization of water molecules present in water-diesel emulsion. Further, it is observed that the addition of nanoparticles increases the NO_x emission [7]. Among all the prepared fuel, E10TiO₂70 shows the maximum amount of NO_x emission at all compression ratios. This can be due to increase in peak cycle temperature with the addition of nanoparticles.

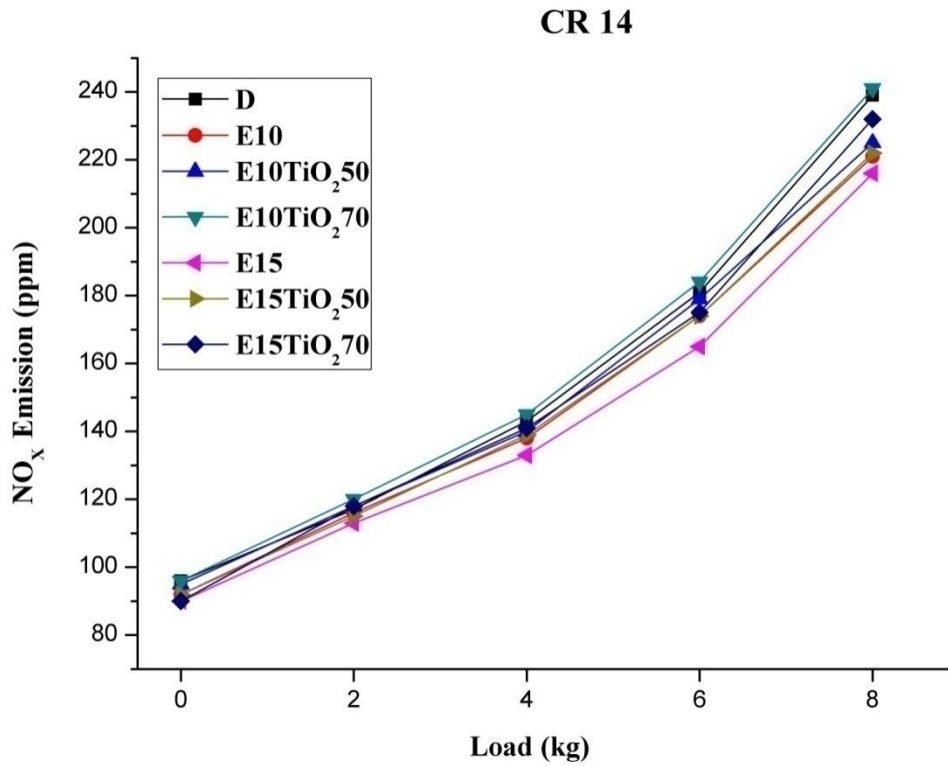


Figure 5.20: Variation of NO_x emission with respect to load at CR 14.

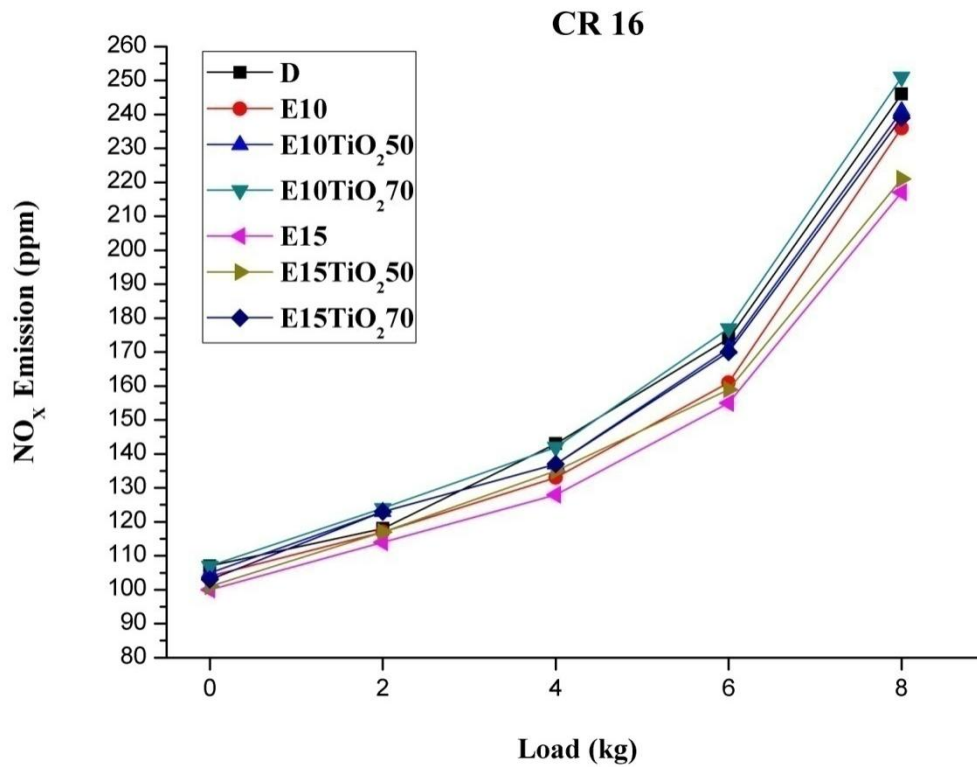


Figure 5.21: Variation of NO_x emission with respect to load at CR 16.

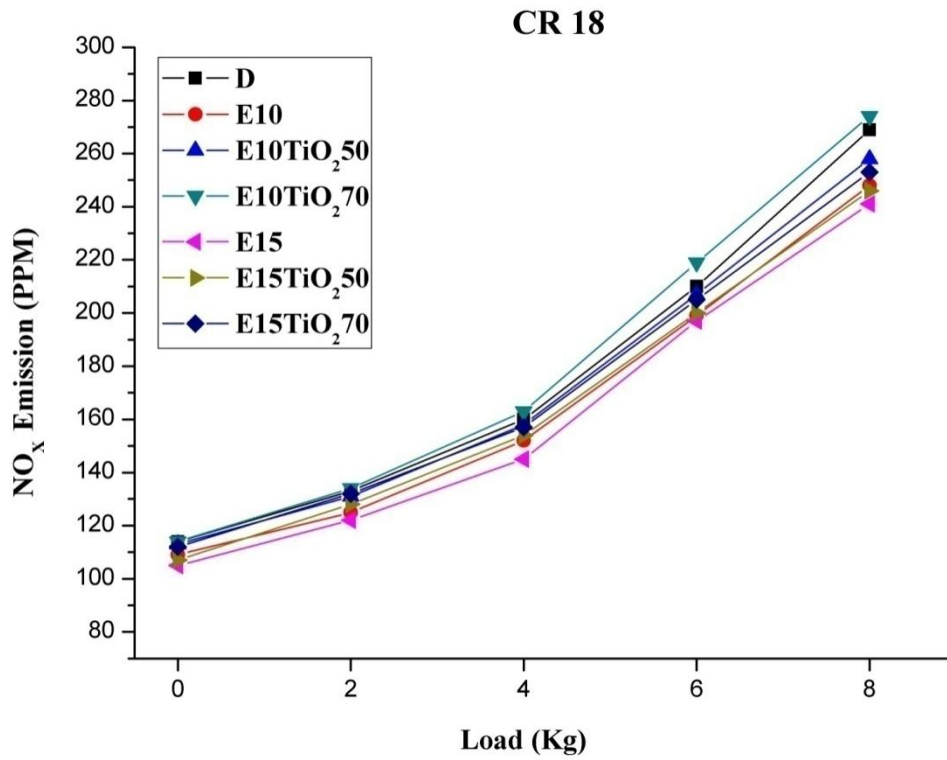


Figure 5.22: Variation of NO_x emission with respect to load at CR 18.

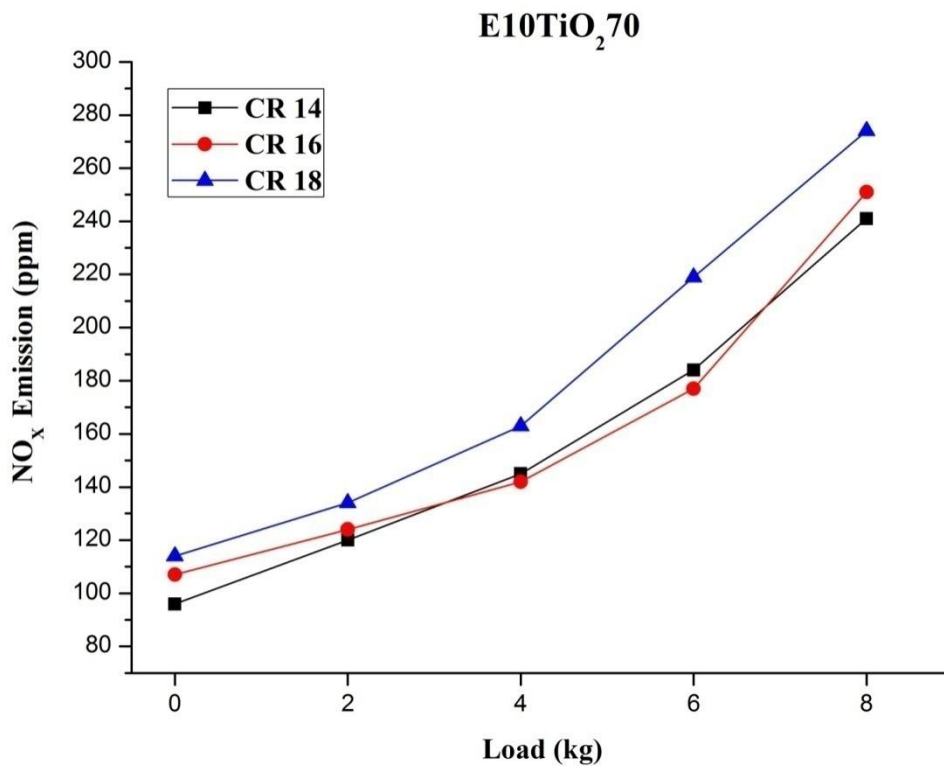


Figure 5.23: NO_x emission variation for E10TiO₂.70 at CR 14, 16 and 18.

- **Effect of compression ratio on NO_x emission**

The variation of NO_x emission for E10TiO₂70 at compression ratio 14, 16 and 18 is shown in figure 5.23. Increase in NO_x emission is noticed with the increase in compression ratio. E10TiO₂70 at compression ratio 18 shows 9.1 % and 13.6 % higher NO_x emission as compared to compression ratio 16 and 14, respectively. This can be due to increase in temperature of air after compression stroke and increased peak cycle temperature with the increase in compression ratio. The variation of NO_x emission for all the fuels with respect to compression ratio at full load is shown in table 5.5.

Table 5.5: NO_x emission (ppm) at CR 14, 16 and 18 corresponding to full load.

CR	D	E10	E10TiO ₂ 50	E10TiO ₂ 70	E15	E15TiO ₂ 50	E15TiO ₂ 70
14	239	221	225	241	216	222	232
16	246	236	241	251	217	221	239
18	269	248	258	274	241	246	253

5.3.2. Hydrocarbon (HC) Emission

- **Effect of blends and load on HC emission**

The main reason behind the formation of unbrunt hydrocarbon emission from compression ignition engine is incomplete combustion of heterogeneous mixture due to formation of local rich mixture spots. The variation of unbrunt hydrocarbon emission with respect to load at compression ratios 14 for pure diesel, E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50 and E15TiO₂70 is shown in figure 5.24. Whereas, figure 5.25 and 5.26 shows the variation at compression 16 and 18, respectively. It is observed from above mentioned figures that the water-diesel emulsion with 15% water content produce higher amounts of hydrocarbon emission as compared to other fuels. This can be due to the presence of water, which decrease localized temperature in the combustion chamber. Moreover, longer ignition delay and higher viscosity of E15 can also be responsible for increase in unbrunt hydrocarbon emission [6]. Further, it is observed that the addition of nanoparticles helps in the reduction of hydrocarbon emission. Among all the prepared fuel, E10TiO₂70 shows the least amount of hydrocarbon emission at all compression ratios. This can be due to improvement in combustion with the addition of nanoparticles.

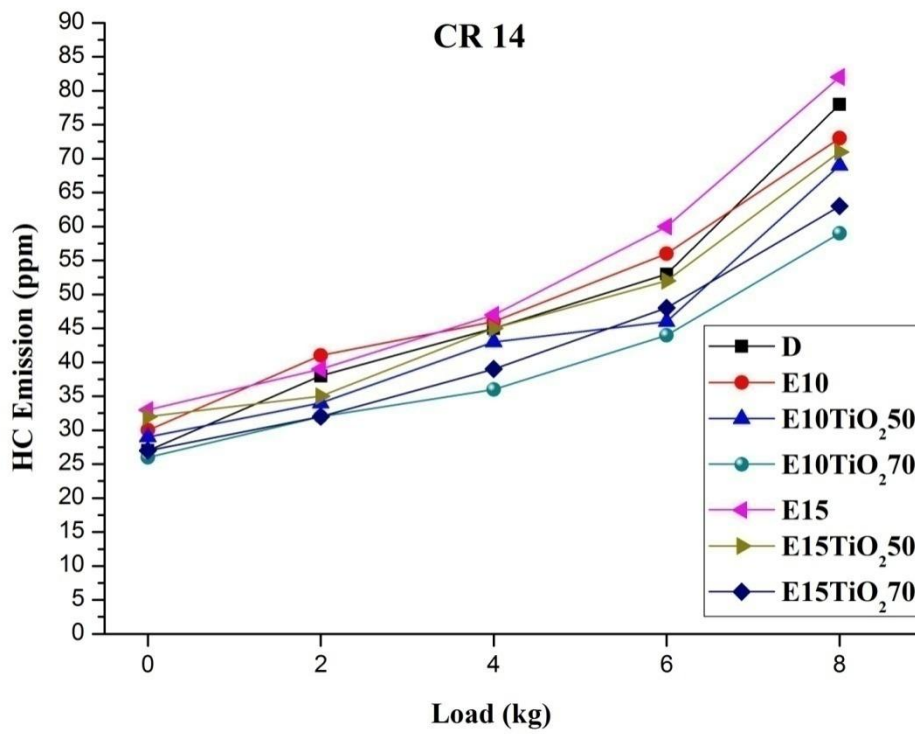


Figure 5.24: Variation of HC emission with respect to load at CR 14.

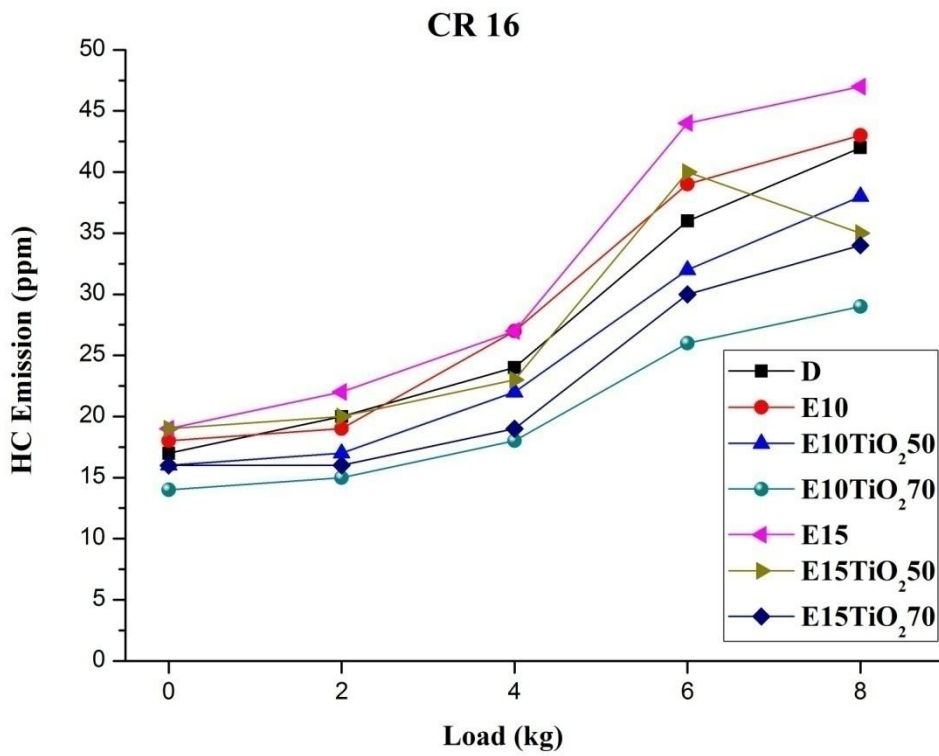


Figure 5.25: Variation of HC emission with respect to load at CR 16.

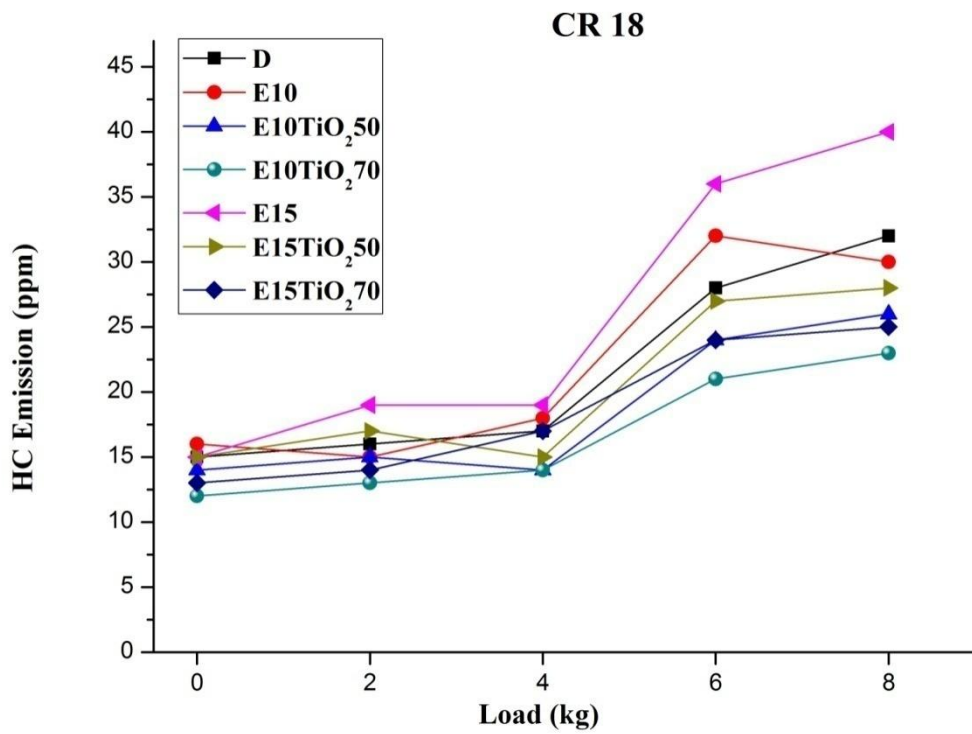


Figure 5.26: Variation of HC emission with respect to load at CR 18.

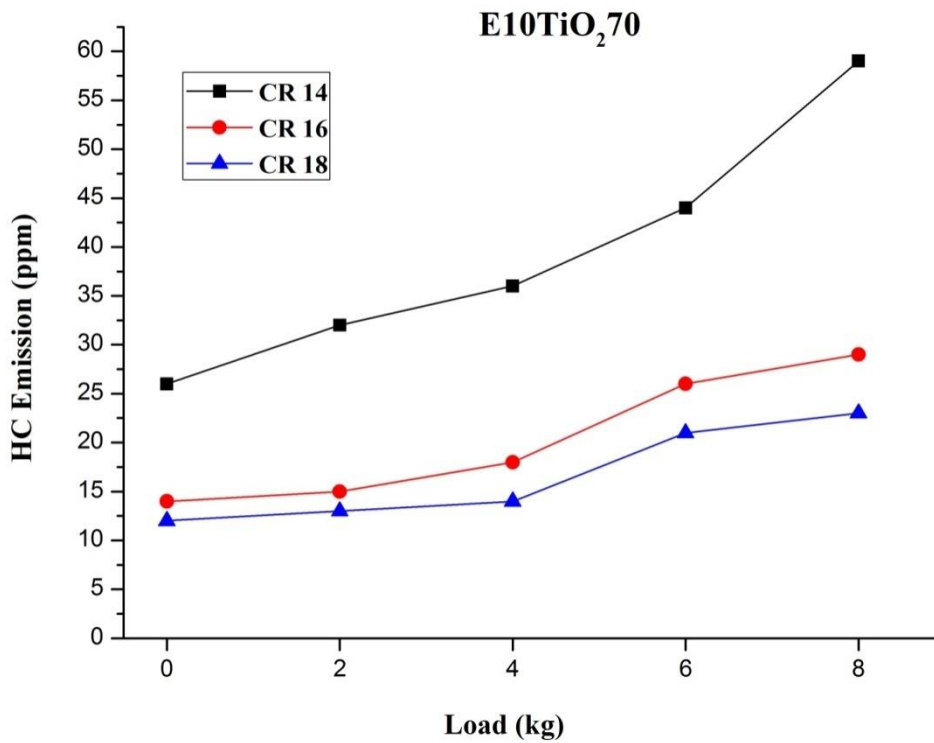


Figure 5.27: HC emission variation for E10TiO₂.70 at CR 14, 16 and 18.

- **Effect of compression ratio on HC emission**

Figure 5.26 shown the reduction in unbrunt hydrocarbon emission with the increase in compression ratios and the minimum HC is obtained with E10TiO₂70 at compression ratio 18. E10TiO₂70 at compression ratio 18 shows 50.8 % and 61 % reduction in HC emission as compared to compression ratio 16 and 14, respectively. Lower HC emission at compression ratio 18 can be due to better atomization, shorter ignition delay and improvement in combustion of fuel because of the higher temperature of air after compression stroke. The effect of compression ratio at full load for all fuels is shown in table 5.6.

Table 5.5: HC emission (ppm) at CR 14, 16 and 18 corresponding to full load.

CR	D	E10	E10TiO ₂ 50	E10TiO ₂ 70	E15	E15TiO ₂ 50	E15TiO ₂ 70
14	78	73	69	59	82	71	63
16	42	43	38	29	47	35	34
18	32	30	26	23	40	28	25

5.3.3. Carbon Monoxide (CO) emission

- **Variation of CO with respect to load**

The CO emission for diesel, E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50 and E15TiO₂70 at varying load and a compression ratio (14, 16 and 18) is demonstrated in figure 5.27, 5.28 and 5.29. Rise in CO emission is observed with increase in load for all the prepared fuels and diesel. It is also found that CO emission of E15 and E10 is higher than diesel [3, 4, 6]. This increase in CO emission is due to short oxygenating time for CO gas because of reduction in temperature of combustion products. This reduction in temperature is due to the presence of water in the combustion chamber. The reduction in the amount of CO emission is found with the addition of nanoparticles. Further, it is noted that CO emission decrease with the dosing level of a titanium oxide nanoparticle in both E10 and E15. Among all the prepared fuels, E10TiO₂70 shows minimum CO emission at compression ratio 18, which is nearly 7.6% lower than diesel. This can be due to the presence of nanoparticles.

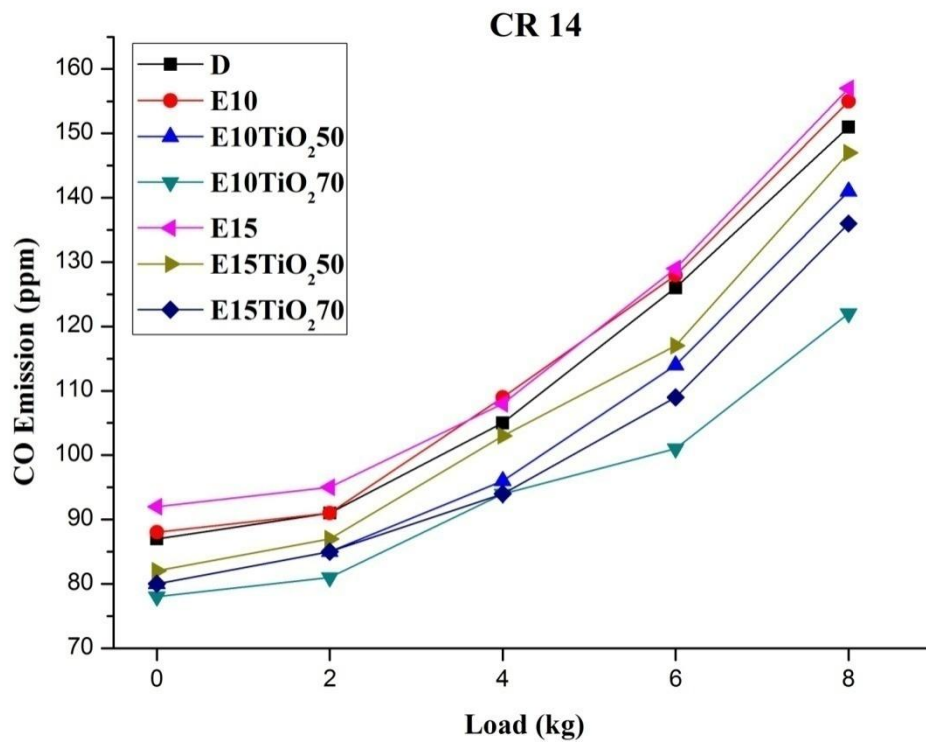


Figure 5.28: Variation of CO emission with respect to load at CR 14.

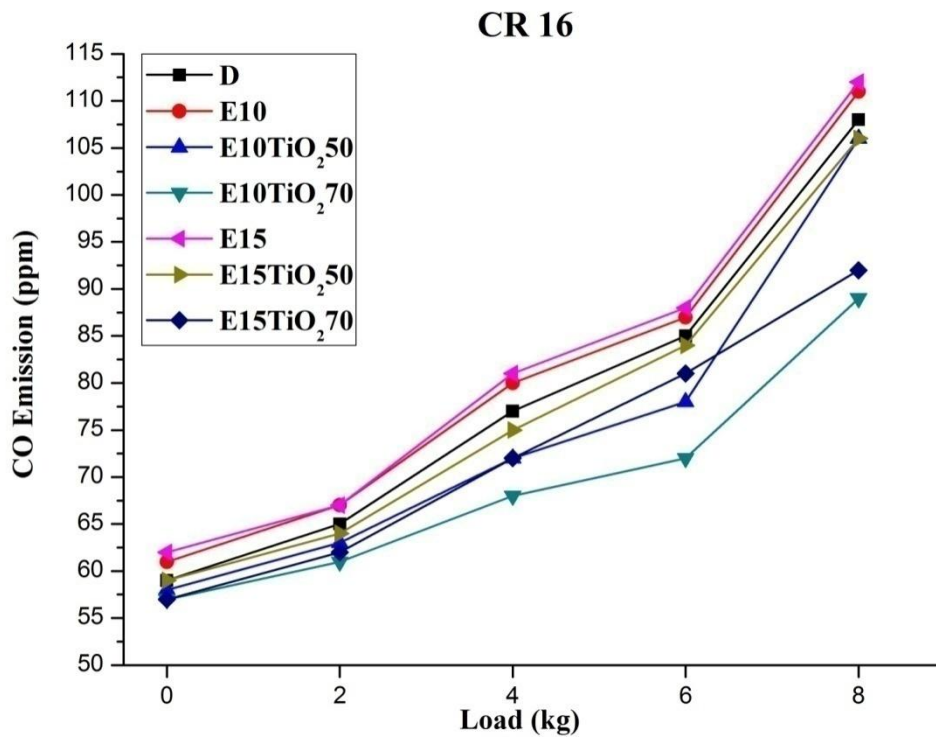


Figure 5.29: Variation of CO emission with respect to load at CR 16.

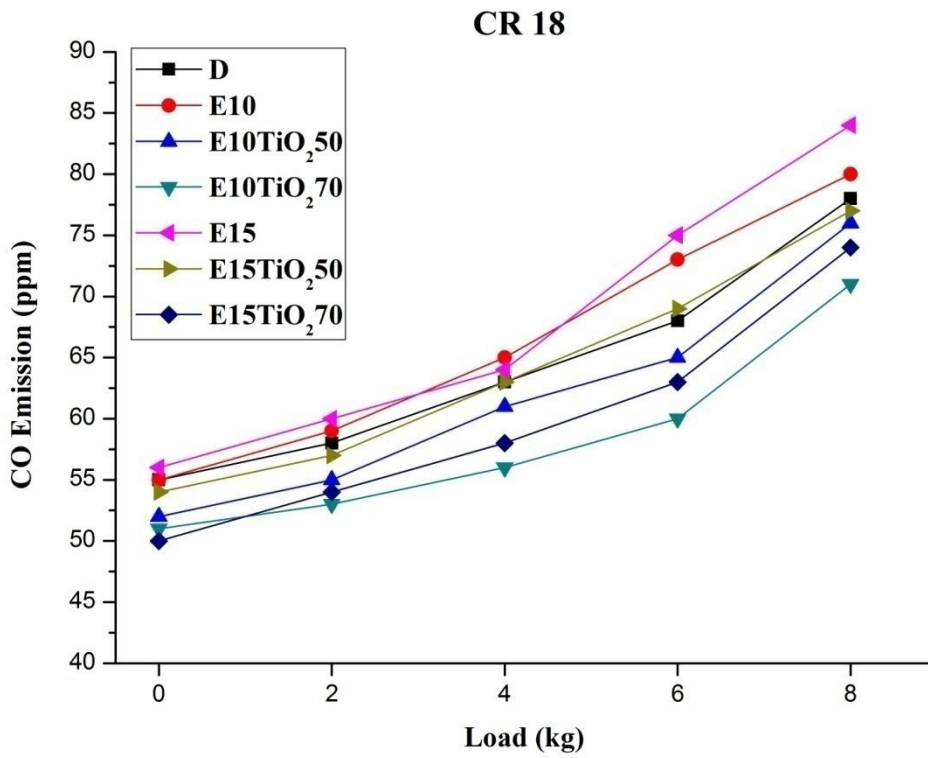


Figure 5.30: Variation of CO emission with respect to load at CR 18.

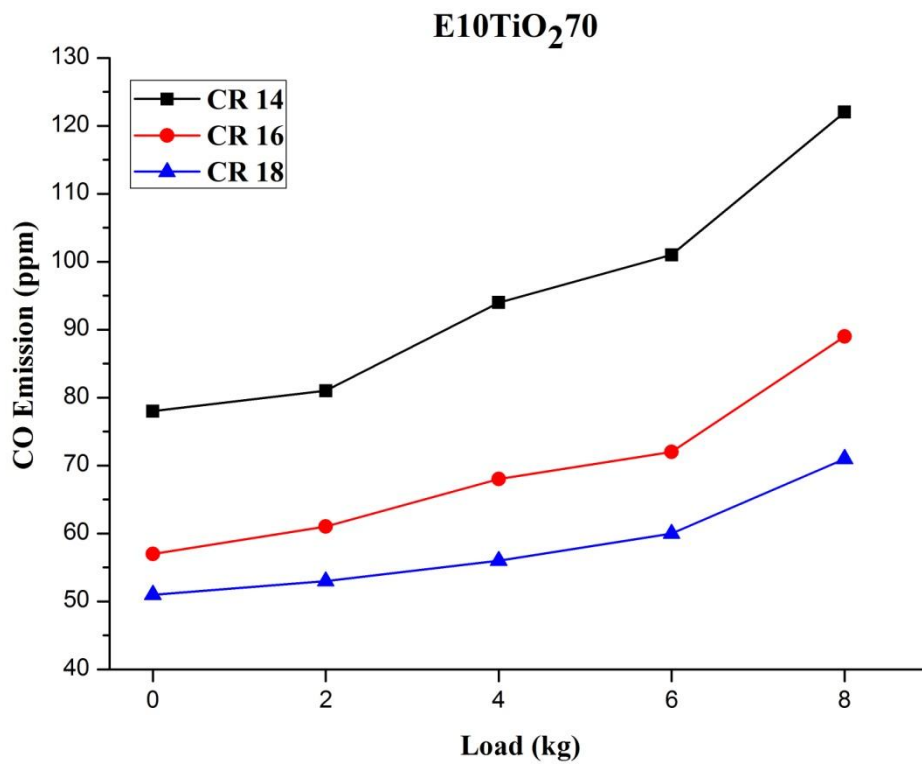


Figure 5.31: CO emission variation for E10TiO₂70 at CR 14, 16 and 18.

- **Effect of compression ratio on CO emission**

Effect of compression ratio on CO emission is shown in figure 5.30. Minimum CO emission is observed at compression ratio 18. Decrease in CO emission is found with the increase in compression ratio. The marginal improvement in CO emission with increase in compression ratio can be due to better mixing of air and fuel in combustion chamber and higher combustion temperature at higher compression ratio. The fuel blend E10TiO₂70 shows least CO emission at compression ratio 18. The variation of CO emission for all the fuels with respect to compression ratio at full load is shown in table 5.7.

Table 5.7: CO emission (ppm) at CR 14, 16 and 18 corresponding to full load.

CR	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
14	151	155	141	122	157	147	136
16	108	111	106	89	112	106	92
18	78	80	76	71	84	77	74

References

- [1] M. Y. E. Selim, M. T. Ghannam, Combustion Study of Stabilized Water-in-Diesel Fuel Emulsion Combustion Study of Stabilized Water-in-Diesel Fuel Emulsion, *Environmental Effects* 7036 (2015) 256-274.
- [2] M. E. L. Kassaby, M. A. Nemit, Studying the effect of compression ratio on an engine fueled with waste oil produced biodiesel/diesel fuel, *Alexandria Engineering Journal* 52 (2013) 1–11.
- [3] C. Lin, L. Chen, Comparison of fuel properties and emission characteristics of two-phase and three-phase emulsions prepared by ultrasonically vibrating and mechanically homogenizing emulsification methods, *Fuel* 0016 (2008) 2154-2161.
- [4] C.Y. Lin, K.H. Wang, Diesel engine performance and emission characteristics using three-phase emulsions as fuel, *Fuel* 83 (2004) 537–545.
- [5] N. S. Kumar, M. S. Kumar, Investigation on the performance and emission characteristics of a diesel engine using water-diesel-nano fluid emulsion as fuel, *Journal of Chemical and Pharmaceutical Sciences* 6 (2015) 37–40.
- [6] J. S. Basha, R. B. Anand, J. S. Basha, R. B. Anand, An Experimental Study in a CI Engine Using Nanoadditive Blended Water–Diesel Emulsion Fuel, *International Journal of Green Energy* 8 (2011) 332-348.
- [7] C. S. Aalam, C. G. Saravanan, M. Kannan, Experimental investigations on a CRDI system assisted diesel engine fuelled with aluminium oxide nanoparticles blended biodiesel, *Alexandria Engineering Journal* 54 (2015) 351-358.

Chapter 6

Conclusion and Future Scope

6.1. Conclusion

The main objective of the present work is the comparative analysis of water diesel emulsion with and without titanium oxide nanoparticles on the basis of performance and emission characteristics of four stroke, single cylinder, VCR diesel engine. For this purpose, six fuel blends (E10, E10TiO₂50, E10TiO₂70, E15, E15TiO₂50 and E15TiO₂70) were prepared and tested. Finally, the results obtained from them are compared with conventional diesel. All the conclusions are drawn on the basis of the experimental results obtained corresponding to full load. The comparison is done on the basis of fuel properties, performance characteristics and emission characteristics.

1. Fuel Properties

- The viscosity shows linear relation to concentration of nanoparticles. The increase in viscosity of both E10 and E15 is observed with the addition of titanium oxide nanoparticles.
- Reduction in the calorific value of diesel with the addition water is viewed as its drawback. The improvement in calorific value of both E10 and E15 is observed with the addition of titanium oxide nanoparticles.

2. Performance characteristics

- A marginal increase in brake power is observed with the addition of titanium oxide nanoparticles. Among all the prepared fuels, E10TiO₂70 shows maximum brake power.
- As compared to other fuels, E10TiO₂70 shows higher brake thermal efficiency. Nearly 3.89 % improvement in brake thermal efficiency is observed with E10TiO₂70 at compression ratio 18.
- The TiO₂ nanoparticle blended water-diesel emulsion shows lower fuel consumption as compare to water-diesel emulsion without nanoparticles. The minimum fuel consumption (0.68 kg/h) is obtained with E10TiO₂70 at compression ratio 18.

- Improvement in brake specific fuel consumption is observed with the addition of TiO₂ nanoparticles. The lowest brake specific fuel consumption (0.30 kg/kWh) is observed with E10TiO₂70 at compression ratio 18.

3. Emission characteristics

- Minimum NO_x emissions are obtained with E15 at compression ratio 14 due to the presence of water in combustion chamber. Further, increase in NO_x emissions are observed with the addition of TiO₂ nanoparticles. As compared to conventional diesel, slightly higher NO_x emissions are observed in the case of E10TiO₂70 but this can be neglected due to other positive effects of E10TiO₂70.
- Higher in HC emission are obtained with E15. However, reduction in HC emission is observed with the addition of TiO₂ nanoparticles. Further, the reduction in HC emission is also observed with the increase in compression ratio. Among all the fuels, E10TiO₂70 shows minimum HC emission (23 ppm) at compression ratio 18.
- As compared to conventional diesel, higher CO emission is observed in the case of water diesel emulsion. However, the addition of TiO₂ nanoparticle results in lower CO emission. E10TiO₂70 shows minimum amount of CO emission (71 ppm) at compression ratio 18.

According to above results, E10TiO₂70 shows higher performance and lower emissions at compression ratio 18 in comparison to other fuels. Based upon the above results, it is concluded that E10TiO₂70 shows promising results on the CI engine performance and emission.

6.2. Scope for future work

- Settlement of nanoparticles is the main problem, which limits its use in diesel, biodiesel as well as in water-diesel emulsion. Therefore, there is a need to find better surfactant or techniques, which ensure higher stability of nanoparticles in all the above-mentioned fuels.
- So far, all the experiments have only shown the effect of alternative fuels on enhancement in the performance of engine like brake specific fuel consumption, brake thermal efficiency, and exhaust emissions. However, none of these experiments has given an insight on the long-term effects that these fuels may have on the engine that is piston, cylinder and ring wear, injector nozzle wear and the level of contamination of engine oil taking place.

- Another point of concern is the effect of nanoparticles used in the fuel on exhaust gas and its impact on the environment.
- Recovery of the nanoparticles from exhaust emission is also the major challenge.

All the above-mentioned points are needed to be investigated carefully to deeply understand the influence of nanoparticle blended water diesel emulsion on CI engines. Further, more experiment investigation are needed, to optimize nanoparticle blended water diesel emulsion for commercialization.

Appendix

A) Nanoparticles

Table A.1: Titanium oxide nanoparticle specification

Purity	99.97%
Average particle size	10 -25 nm
Bulk density	0.15-0.25 g/cm ³
True density	3.9 g/cm ³
Colour	White

B) Fuel Properties

Table B.1: Various properties of fuels

Fuels	Properties			
	Calorific value (kJ/kg)	Density (g/cc)	Viscosity (mm ² /sec)	Flash point (°C)
D	44630	0.8298	2.5	55
E10	39788	0.8435	4.13	66
E10TiO₂50	40893	0.8442	4.19	69
E10TiO₂70	41689	0.8447	4.23	71
E15	37457	0.8504	4.81	69
E15TiO₂50	38653	0.8512	4.88	72
E15TiO₂70	39987	0.8516	4.91	75

C) Experimental Data of Engine Performance Test

Brake Power (BP)

Table C.1: Results of BP (KW) for all fuels at different loads and compression ratio 14

Compression Ratio 14							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0	0	0	0	0	0	0
2	0.57	0.56	0.56	0.58	0.55	0.56	0.56
4	1.13	1.12	1.13	1.15	1.11	1.12	1.14
6	1.67	1.65	1.67	1.69	1.64	1.65	1.68
8	2.17	2.15	2.16	2.20	2.14	2.17	2.18

Table C.2: Results of BP (KW) for all fuels at different loads and compression ratio 16

Compression Ratio 16							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0	0	0	0	0	0	0
2	0.58	0.57	0.59	0.6	0.56	0.57	0.58
4	1.13	1.12	1.13	1.15	1.12	1.13	1.14
6	1.68	1.67	1.69	1.70	1.68	1.68	1.69
8	2.22	2.21	2.21	2.22	2.2	2.19	2.21

Table C.3: Results of BP (KW) for all fuels at different loads and compression ratio 18

Compression Ratio 18							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0	0	0	0	0	0	0
2	0.6	0.59	0.62	0.63	0.59	0.6	0.61
4	1.15	1.13	1.16	1.18	1.13	1.16	1.18
6	1.69	1.68	1.71	1.73	1.67	1.67	1.69
8	2.22	2.21	2.23	2.25	2.20	2.22	2.23

Brake thermal efficiency (BTE)

Table C.4: Results of BTE (%) for all fuels at different loads and compression ratio 14

Compression Ratio 14							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0	0	0	0	0	0	0
2	8.18	8.33	9.6	9.7	8.25	8.79	9.15
4	14.31	15.49	16.62	17.12	15.31	15.54	15.76
6	18.37	19.94	20.66	22.71	19.14	20.14	20.4
8	19.94	21.33	23.50	24.03	20.96	21.64	23.07

Table C.5: Results of BTE (%) for all fuels at different loads and compression ratio 16

Compression Ratio 16							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0	0	0	0	0	0	0
2	8.65	9.52	10.03	11.4	9.43	9.63	9.66
4	15.3	15.98	16.81	17.39	15.56	16.08	16.47
6	18.67	19.55	21.37	22.6	19.14	19.83	20.11
8	21.16	21.47	24.25	24.90	21.31	21.73	21.97

Table C.6: Results of BTE (%) for all fuels at different loads and compression ratio 18

Compression Ratio 18							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0	0	0	0	0	0	0
2	9.66	10.82	11.11	12.60	10.6	10.93	11.02
4	15.27	16.88	18.02	18.62	17.09	16.95	17.12
6	19.67	20.80	22.39	23.45	20.63	21.52	21.70
8	24.30	24.43	25.05	28.19	24.12	24.84	25.87

Fuel Consumption (FC)

Table C.7: Results of FC (kg/h) for all fuels at different loads and compression ratio 14

Compression Ratio 14							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0.39	0.50	0.50	0.45	0.50	0.55	0.45
2	0.56	0.60	0.51	0.51	0.64	0.59	0.55
4	0.63	0.65	0.59	0.58	0.69	0.67	0.65
6	0.73	0.74	0.71	0.64	0.82	0.76	0.74
8	0.87	0.91	0.80	0.79	0.98	0.93	0.85

Table C.8: Results of FC (kg/h) for all fuels at different loads and compression ratio 16

Compression Ratio 16							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0.34	0.39	0.40	0.40	0.35	0.40	0.40
2	0.54	0.54	0.51	0.45	0.57	0.55	0.54
4	0.59	0.63	0.59	0.57	0.69	0.65	0.62
6	0.72	0.77	0.69	0.64	0.84	0.78	0.75
8	0.84	0.93	0.80	0.76	0.99	0.93	0.90

Table C.9: Results of FC (kg/h) for all fuels at different loads and compression ratio 18

Compression Ratio 18							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	0.34	0.40	0.35	0.35	0.30	0.40	0.40
2	0.50	0.49	0.49	0.43	0.53	0.51	0.49
4	0.60	0.60	0.56	0.54	0.63	0.63	0.62
6	0.69	0.73	0.67	0.63	0.77	0.72	0.70
8	0.73	0.81	0.78	0.68	0.87	0.83	0.77

Brake Specific Fuel Consumption (BSFC)

Table C.10: Results of BSFC (kg/kWh) for all fuels at different loads and compression ratio 14

Compression Ratio 14							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
2	0.98	1.07	0.91	0.87	1.16	1.05	0.98
4	0.55	0.58	0.52	0.50	0.62	0.59	0.57
6	0.43	0.44	0.42	0.37	0.50	0.46	0.44
8	0.40	0.42	0.37	0.35	0.45	0.42	0.38

Table C.11: Results of BSFC (kg/kWh) for all fuels at different loads and compression ratio 16

Compression Ratio 16							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
2	0.93	0.94	0.86	0.75	1.01	0.96	0.93
4	0.52	0.56	0.52	0.49	0.61	0.57	0.54
6	0.42	0.46	0.40	0.37	0.50	0.46	0.44
8	0.37	0.42	0.36	0.34	0.45	0.42	0.40

Table C.12: Results of BSFC (kg/kWh) for all fuels at different loads and compression ratio 18

Compression Ratio 18							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
2	0.83	0.83	0.79	0.68	0.89	0.85	0.80
4	0.52	0.53	0.48	0.45	0.55	0.54	0.52
6	0.40	0.43	0.39	0.36	0.46	0.43	0.41
8	0.32	0.36	0.34	0.30	0.39	0.37	0.34

D) Experimental Data of Engine Emission Test

NO_x Emission

Table D.1: Results of NO_x (ppm) for all fuels at different loads and compression ratio 14

Compression Ratio 14							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	96	92	95	96	90	92	90
2	117	116	118	120	113	115	118
4	143	138	140	145	133	139	141
6	181	174	179	184	165	174	175
8	239	221	225	241	216	222	232

Table D.2: Results of NO_x (ppm) for all fuels at different loads and compression ratio 16

Compression Ratio 16							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	107	104	105	107	100	101	103
2	118	117	123	124	114	117	123
4	143	133	137	142	128	135	137
6	174	161	171	177	155	159	170
8	246	236	241	251	217	221	239

Table D.3: Results of NO_x (ppm) for all fuels at different loads and compression ratio 18

Compression Ratio 18							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	114	109	113	114	105	107	112
2	133	125	131	134	122	128	132
4	160	152	158	163	145	154	157
6	210	199	207	219	197	200	205
8	269	248	258	274	241	246	253

CO emission

Table D.4: Results of CO (ppm) for all fuels at different loads and compression ratio 14

Compression Ratio 14							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	87	88	80	78	92	82	80
2	91	91	85	81	95	87	85
4	105	109	96	94	108	103	94
6	126	128	114	101	129	117	109
8	151	155	141	122	157	147	136

Table D.5: Results of CO (ppm) for all fuels at different loads and compression ratio 16

Compression Ratio 16							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	59	61	58	57	62	59	57
2	65	67	63	61	67	64	62
4	77	80	72	68	81	75	72
6	85	87	78	72	88	84	81
8	108	111	106	89	112	106	92

Table D.6: Results of CO (ppm) for all fuels at different loads and compression ratio 18

Compression Ratio 18							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	55	55	52	51	56	54	50
2	58	59	55	53	60	57	54
4	63	65	61	56	64	63	58
6	68	73	65	60	75	69	63
8	78	80	76	71	84	77	74

HC emission

Table D.7: Results of HC (ppm) for all fuels at different loads and compression ratio 14

Compression Ratio 14							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	27	30	29	26	33	32	27
2	38	41	34	32	39	35	32
4	45	46	43	36	47	45	39
6	53	56	46	44	60	52	48
8	78	73	69	59	82	71	63

Table D.8: Results of HC (ppm) for all fuels at different loads and compression ratio 16

Compression Ratio 16							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	17	18	16	14	19	19	16
2	20	19	17	15	22	20	16
4	24	27	22	18	27	23	19
6	36	39	32	26	44	40	30
8	42	43	38	29	47	35	34

Table D.9: Results of HC (ppm) for all fuels at different loads and compression ratio 18

Compression Ratio 18							
Load	D	E10	E10TiO₂50	E10TiO₂70	E15	E15TiO₂50	E15TiO₂70
0	15	16	14	12	15	15	13
2	16	15	15	13	19	17	14
4	17	18	14	14	19	15	17
6	28	32	24	21	36	27	24
8	32	30	26	23	40	28	25