

## **ABSTRACT**

SRIRAM, SUBASH. Performance and Emissions Testing of Mixtures of Diesel Extracts of Bio-oil and Eugenol in Diesel. (Under the direction of Dr. Tiegang Fang.)

Internal combustion engines have been an integral part of modern civilization and have been responsible for the advancement of different sectors ranging from transportation to agriculture. Their dominance has been under question during the past decades with the argument that they continue to mainly use fossil fuels. Fossil fuels are non-renewable and also cause a lot of pollution as a result of their emissions which can lead to dire consequences. Currently, engines cannot be completely replaced with any new technology that solves the issues of finite fuel supply and pollution. They need to be improved with respect to their source of energy, so as to smoothly transition to more sustainable alternatives.

This thesis is an investigation of a few possible alternative fuel sources that might help move towards renewable and clean energy for internal combustion engines. A compression ignition engine test cell was used for this objective. The first experiment was conducted using a mixture of diesel extracts of bio-oil in diesel. A process of liquid-liquid extraction was carried out on wood pyrolysis oil. The performance of this fuel was comparable to that of commercial diesel and it was superior to diesel in terms of fuel consumption, at moderate load conditions. Hydrocarbon and NO<sub>x</sub> emissions were reduced with the use of this fuel.

The next experiment was to investigate the effect of eugenol, which was a major component in the mixture tested in the previous experiment. Eugenol was mixed with diesel in different proportions and its performance and emissions during combustion was tested. It was seen that this mixture too was comparable to diesel in terms of performance but

consumed more fuel than when diesel was used. There was a reduction in hydrocarbon and soot concentrations but NO<sub>x</sub> levels at high loads were observed to be higher than with the use of diesel. This study provided new insights into the use of eugenol as a mixture with diesel at relatively higher concentrations.

It is clear that bio-oil based fuels have the potential to reduce pollutant emissions from engines when compared to diesel. However, the fuel consumption was higher in the case of eugenol mixtures and it reduced emissions only in a few cases. Further experimentation with different concentrations and different organic components make-up is needed to verify these findings. Novel methods of using diesel and bio-diesel in liquid-liquid extraction of bi-oil components have been tested successfully. Also, the positive trends observed in this study encourage the testing of these fuels in engines which are closer to large-scale, practical applications and under a wide range of load conditions.

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Performance and Emissions Testing of Mixtures of Diesel Extracts of Bio-oil  
and Eugenol in Diesel

by  
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## **DEDICATION**

*This thesis is dedicated to my parents, my brother and my friends. The boundless love they have showered on me and their steadfast support are the reasons I am the person I am today.*

## **BIOGRAPHY**

Subash was born in Chennai, India in 1992. His schooling stoked his interest towards physics and its applications in everyday life, encouraging him to explore these areas. He completed his Bachelor of Engineering degree in Mechanical Engineering at SSN College of Engineering, Chennai, India in 2014. He was exposed to the field of heat transfer and energy during these years in college. His projects during this time gave him his first taste of research and further increased his interest in energy systems and their applications. Desiring to explore and to understand the state of the art in these areas, he secured admission into North Carolina State University for a Master's degree in Mechanical Engineering as an international graduate student, in 2014. He chose combustion and the study of internal combustion engines as his area of research and started to work under the guidance of Dr. Tiegang Fang at the Spray and Engine Diagnostics laboratory from the Fall of 2014.

## ACKNOWLEDGMENTS

First and foremost, I would like to thank Dr. Tiegang Fang for giving me the opportunity to work in his laboratory under his guidance. His constant support and insightful counsel not only helped me with this project but has also shaped the way I approach a given task and my mindset towards it. He has supported me despite a series of setbacks and stumbles during my time here and for that I am grateful. The things that I have learnt in this research group have shaped me not only as an engineer but also as a person and will continue to do so for the rest of my life.

I would also like to thank my committee members, Dr. Stephen Terry and Dr. Sunkyu Park. Dr. Terry's HVAC course was greatly influential in shaping my interest towards clean energy systems and energy efficiency, which is the ultimate aim of this project. This project would not have been possible without the help from Dr. Sunkyu Park and his research team, especially Dr. Hoyong Kim. Dr. Park provided me with the bio-fuels required for this project, in a timely manner and helped me understand the chemistry behind its synthesis. This was instrumental in helping me draw inferences from the data that I collected and the observation I made.

I am very grateful for the expert craftsmanship exhibited by Mr. Steve Cameron, who heads the MAE department shop. The speed and precision of his work not only allowed me to progress through this project at critical junctures but also gave me an understanding of what goes on behind the design and fabrication of components.

The completion of this project was manageable only with the help and support I received from the other members of my research group. First, I must acknowledge Dolanimi Ogunkoya's useful insights which proved to be priceless. I thank him for being there for me whenever I called him, despite his hectic schedule. Troubleshooting this setup would have been impossible without his help. I am grateful for Libing Wang's and Zengyang Wu's mentorship and guidance during my early days in this group when they showed me the ropes. They were extremely approachable and guided me even with the smallest of tasks, right till the end of this project. I thank Uddhava Jawalkar for helping me with some key logistics and for providing useful tips at crucial points of my research. I would not have been able to handle this test cell and conduct experiments on it without the help of Himanshu Londhe. Not only did he suggest some good ideas to improve this setup but also served as someone who I could bounce ideas off of. All the members of this research group have certainly helped me with this project in more ways than I can recall and for that I express my gratitude to all of them.

I would like to thank my parents, whose love and sacrifice for me are immeasurable. I would also like to thank all my friends, old and new, who saw me through graduate school. Their patient ears and inspiring words helped me bounce back from countless setbacks. The faith that my family and friends have in me, easily surpasses that which I have in myself and it was this faith that pushed me to grow immensely during my time at NC State.

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## **LIST OF ABBREVIATIONS AND SYMBOLS**

**BMEP** - Brake Mean Effective Pressure

**BSFC** – Brake Specific Fuel Consumption

**HC** – Hydrocarbons

**CO** – Carbon monoxide

**CO<sub>2</sub>** – Carbon dioxide

**NO<sub>x</sub>** – Oxides of nitrogen

**O<sub>2</sub>** – Oxygen

**°C** – Degree Celcius

**TDC** – Top Dead Centre

# CHAPTER 1

## INTRODUCTION

Internal Combustion engines, first built in the 18<sup>th</sup> Century, remain till date, one of the main technological advancement for the conversion of chemical energy to other useful forms. These engines have played a major role in the development of the world economy by dominating the transportation sector and continue to do so till date. In 1997, diesel accounted for 95% of the freight ton-miles of the world [1]. Diesel accounts for 22% of the energy consumed by the US transportation sector in the year 2014 [2]. Besides this, three other key sectors that heavily rely on diesel as a fuel are agriculture, construction and mining. The role that diesel and diesel engines play in the modern world is evident and research towards its advancement is justified. It is safe to conclude that diesel engines will remain popular as they also provide certain physical advantages like high efficiency, high power- weight ratio and scalability [3]. Several factors have prompted research not only in improving the performance of diesel engines but in the search for alternative fuels. One key factor is the diminishing fossil fuel reserves on this planet while at the same time, their increasing consumption [4]. It is estimated that world oil reserves will be depleted by the year 2051 and also by the year 2100 the world's energy demand will be five times of what it is today [5]. This calls for immediate and urgent solutions for alternate fuels. Also from a socio-economic standpoint, dependence on a handful of fuels is strategically unstable as was evident in the Energy crisis of the 1970s in the USA. One other major cause for concern regarding diesel engine combustion is its emissions. From a sustainability standpoint, it is our duty to protect

the planet from the ramifications of our development. This is also enforced by governmental agencies in the form of strict emission norms, the most significant of which is the Tier 3 standards for motor vehicles which, starting in 2017 will enforce significant constraints on NO<sub>x</sub>, carbon monoxide and hydrocarbons which are emitted from motor vehicles [6]. These are some of the main emissions from a compression ignition engine. Other Greenhouse Gases are also emitted which contribute to global warming [5]. Rising costs, depleting reserves as well as pollution caused by fossil fuels call for the development of alternative fuels and fuel blends to power compression ignition engines in a sustainable manner without compromising too much on performance [7].

Thus, the objective of this study is investigate possible alternative fuels and understand their behavior in compression ignition engines with an aim of possibly replacing diesel with such fuels or their blends. The key concerns during this investigation will be the fuel's sustainability, its performance and the consequences of its usage. The fuels must be renewable and their performance must be comparable or exceed that of conventional fossil fuels (in this case, diesel) but must certainly result in a reduction in emissions.

## **CHAPTER 2**

### **EXPERIMENTAL SETUP**

The test cell used for this study consists of a diesel engine with appropriate sensors installed to collect the required data. Additionally, a water loading system and an exhaust gas collection system were also implemented.

The diesel engine used is a 10 Horsepower, single cylinder, 4-stroke, air-cooled compression ignition engine with a bore and stroke of 86mm and 72mm respectively and with a 19:1 compression ratio. A picture of this engine is shown in Figure 2.1. A summary of the specifications of this engine is given in Table 2.1. The main modification made to this engine was a threaded hole which was machined into the cylinder head to accommodate the Kistler 6052A pressure sensor, shown in Figure 2.2 a-b, which was used to measure the in-cylinder pressure in real time. In addition to the above mentioned pressure sensor, several other sensors were used to facilitate data acquisition. The most important of these were the Omron E62B Shaft Encoder and the Cherry MP100701 Hall Effect Sensor which in conjunction were incorporated into a gear box attached to the flywheel as can be seen in Figure 2.3 a-b, to accurately determine the Top Dead Centre Position. The Hall Effect sensor also served to measure the speed of the engine.

This engine was loaded using a DY-7D Go-Power Water Brake Dynamometer which is shown in Figure 2.4 a-b. This called for the design and construction of a water supply, return and cooling mechanism which was implemented using two water reservoirs, water pumps, control valves and filters. A load cell connected to a SSI M5100 series Pressure transducer was used to measure the load on the engine. The load cell was connected to the Water Dynamometer's casing arm and would

transmit a perpendicular force proportional to the load on the engine. This can also be seen in Figure 2.4 a-b

The exhaust pipe had a K-Type thermocouple with a Delta DTB 4842 digital readout to measure the exhaust gas temperature. The end of the exhaust tail pipe ended in a hollow T-junction which provided a cylinder of exhaust gas of sufficient length to be used to measure the opacity of the exhaust smoke. A Wager 6500 Smoke meter was used to measure this opacity. A picture of this setup is shown in Figure 2.5 and the specifications of the meter are listed in Table 2.2 To prevent the soot from directly contacting and compromising the sensor, glass panes were set up in a wooden stand. The readings were taken after the device was adjusted for the thickness of the two glass panes. A FGA 4000XDS Gas Analyzer was used to measure the species concentration in the exhaust gas. The species that were measured were HC, CO, CO<sub>2</sub>, and NO<sub>x</sub>. The display of this analyzer can be seen in Figure 2.6 and its specifications are given in Table 2.3. The fuel flow rate was calculated by using a METTLER PM4800 weighing scale.

All the data from the sensors was collected and was acquired by a National Instruments PCI- MIO 16 E4 data acquisition card via a SCB-68 extension pin box. A custom National Instruments LabVIEW program was developed to control this data acquisition. The front panel of this program is shown in Figure 2.8. The collected data was then processed using a Microsoft Excel and MATLAB where custom programs were written and executed.

Table 2.1: Engine Specifications

<b>Engine</b>	Single Cylinder, 4-Stroke, Direct Injection, Vertical Orientation
<b>Compression Ratio</b>	19:1
<b>Bore x Stroke</b>	86mm x 72mm
<b>Method of Loading</b>	Water brake dynamometer
<b>Method of Starting</b>	Electric
<b>Method of Cooling</b>	Air Cooled
<b>Type of Ignition</b>	Compression Ignition
<b>Rated Power</b>	10 HP
<b>Rated Speed</b>	3600 RPM
<b>Initial Injection</b>	17.0 Crank Angle Degrees before TDC
<b>Displacement</b>	418 cc
<b>Fuel Consumption at Rated Power</b>	340 g/kW.hr

Table 2.2: Wager Smoke Meter Specifications

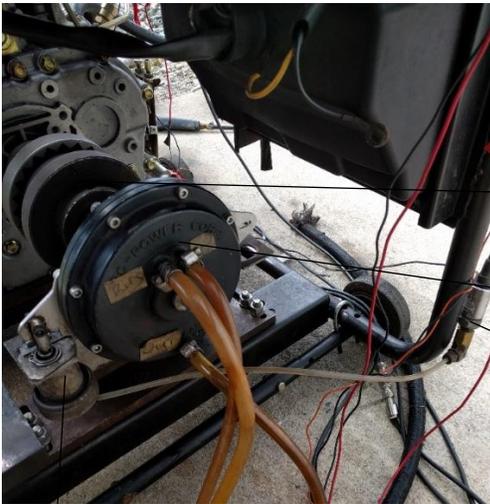
<b>Light Source</b>	LED- Gallium Phosphide 570 nm
<b>Light Sensor</b>	Silicon Photo Diode with Infrared Filter
<b>Opacity Meter Accuracy</b>	+/- 1.0% Nominal, +/-10 <sup>th</sup> digit
<b>Range</b>	0.0% - 100.0% opacity
<b>Response Time</b>	0.45s for 0 – 90% opacity
<b>Linearity</b>	+/- 1% from 0 – 100% opacity

Table 2.3: FGA 4000XDS Gas Analyzer Specifications

<b>Measured Species</b>	<b>Measured Range/ Techniques</b>
HC, CO, CO <sub>2</sub>	Non-Dispersive Infrared (NDIR)
O <sub>2</sub> and NO <sub>x</sub>	Chemical Cell
CO	0 to 10.00%
HC	0 to 10,000 ppm
CO <sub>2</sub>	0 to 20%
O <sub>2</sub>	0 to 25%
NO <sub>x</sub>	0 to 4,000 ppm



(a)



(b)

Shaft Coupling

Water Dynamometer

Pressure Transducer

Load Cell

Figure 2.1a-b: Engine Test Cell Setup

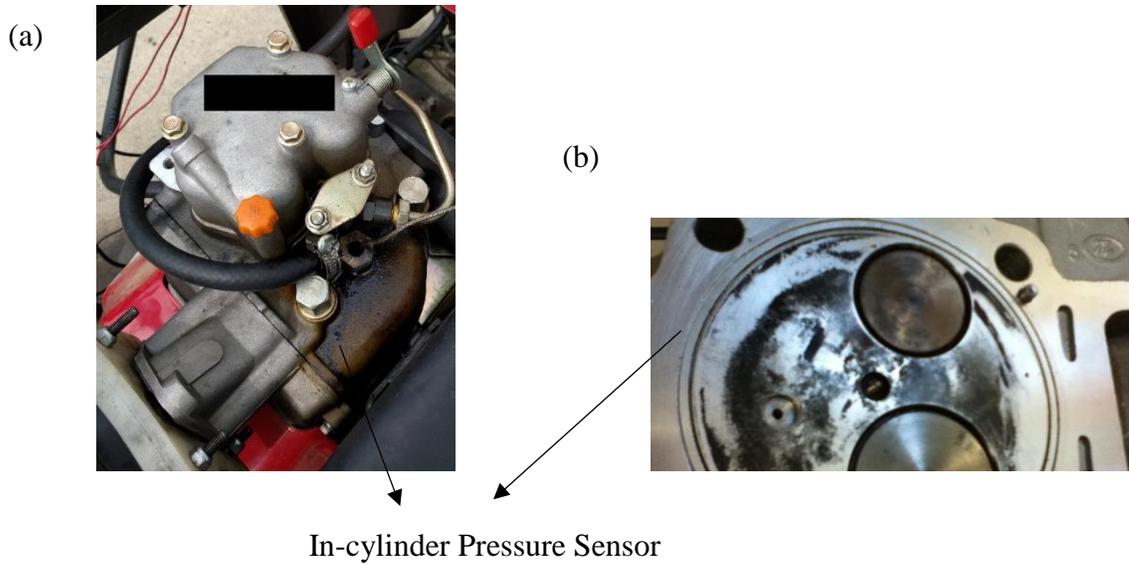


Figure 2.2 a-b: Installation of Kistler 6052-A In-Cylinder Pressure Sensor

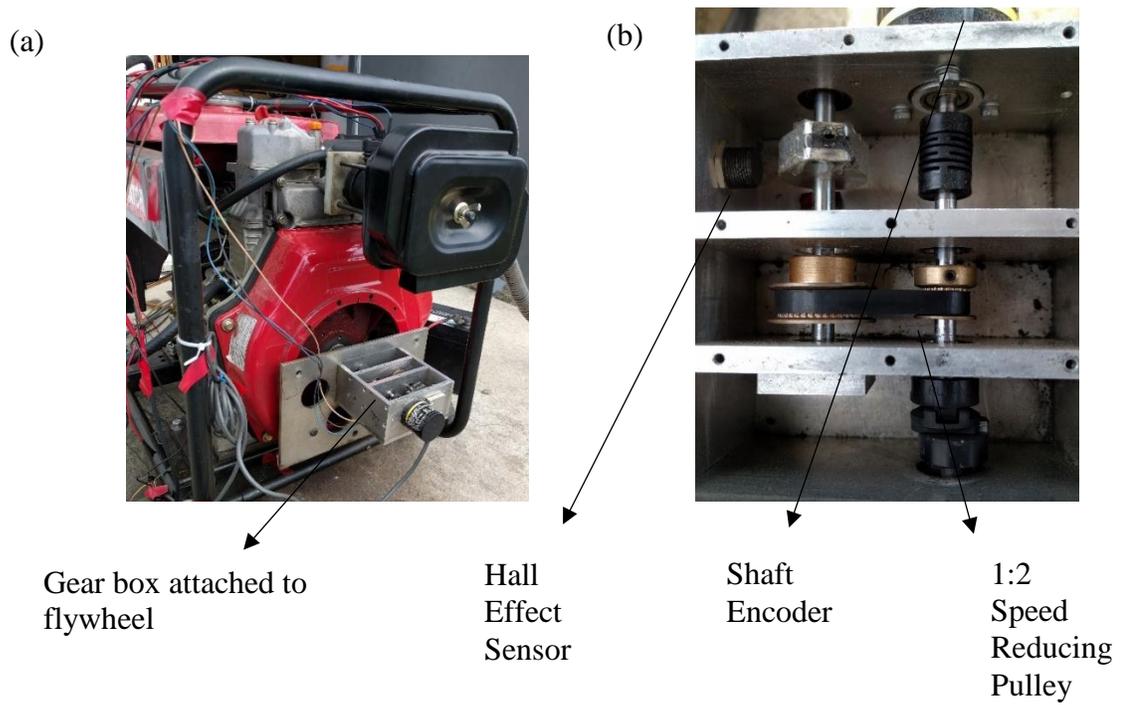


Figure 2.3 a-b: Gear box attached to flywheel

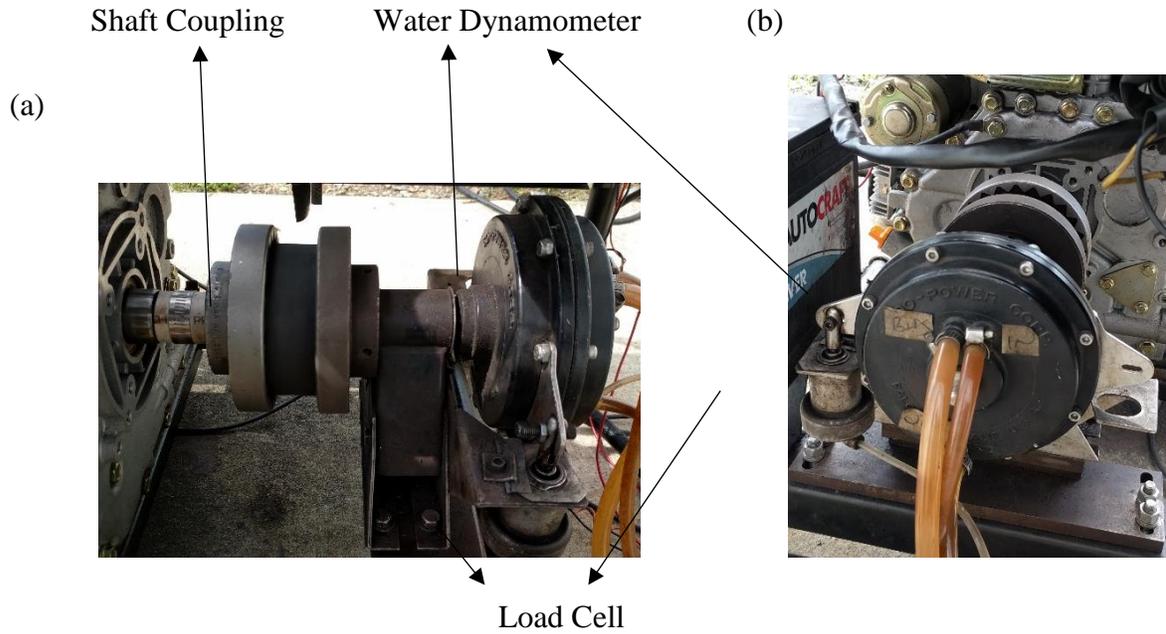


Figure 2.4: Water Dynamometer Setup

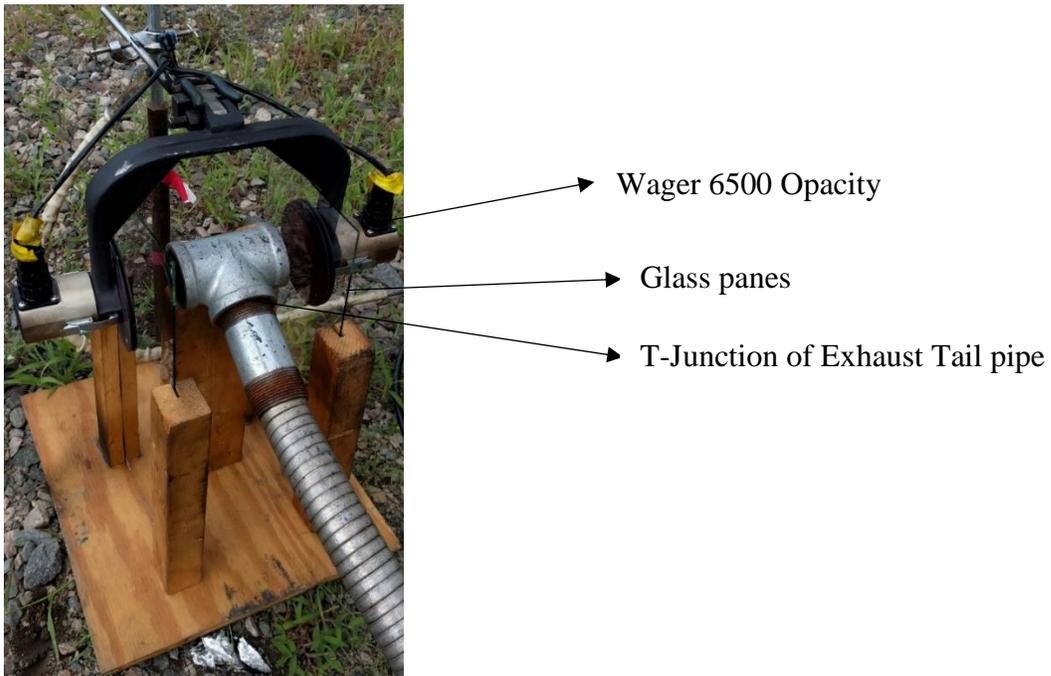


Figure 2.5: Opacity Meter Setup

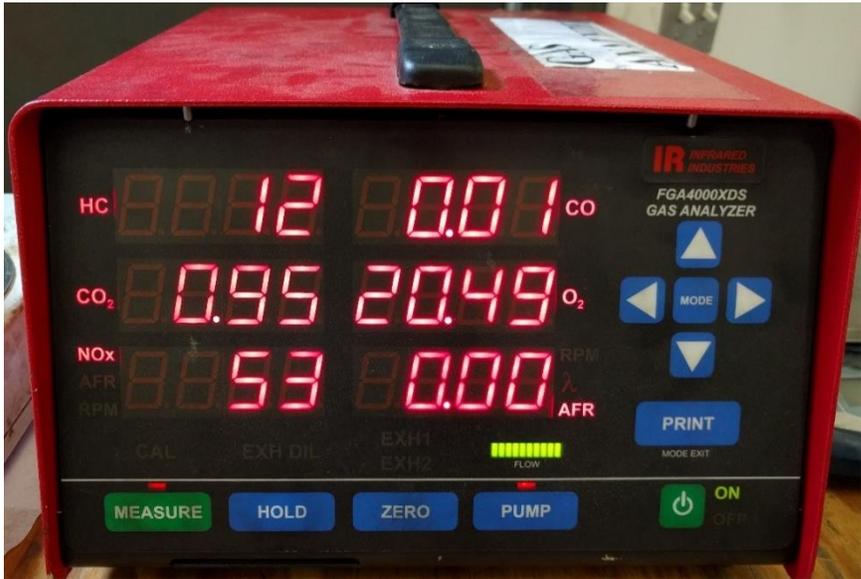


Figure 2.6 : FGA 4000 XDS Gas Analyzer

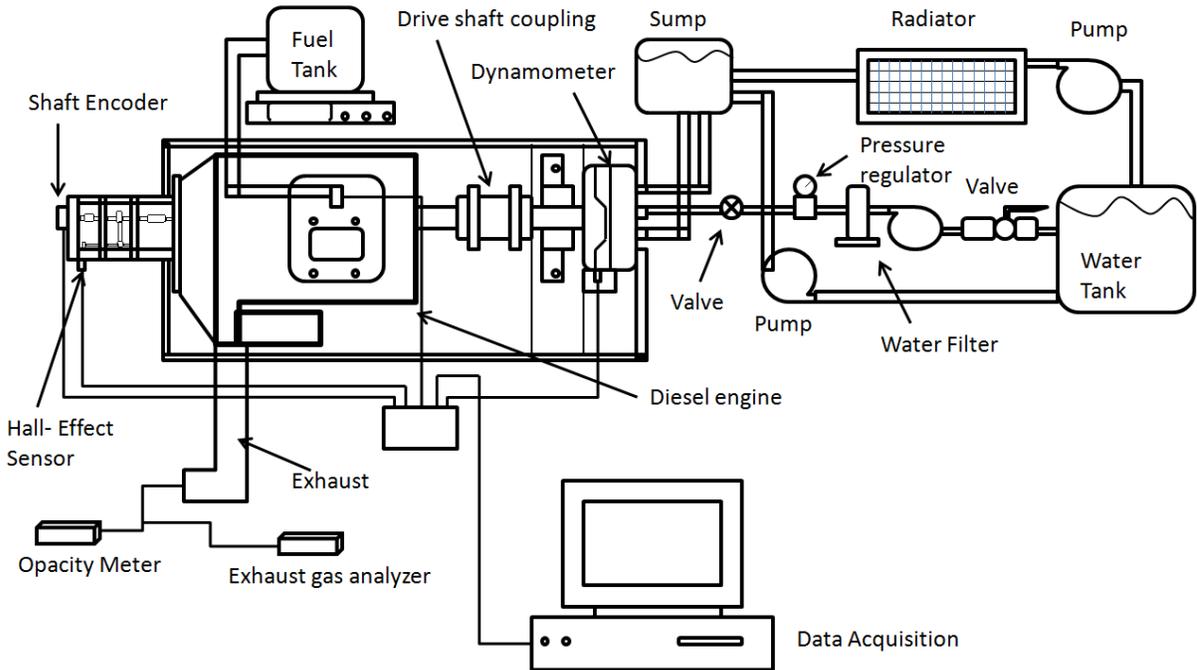


Figure 2.7: Schematic of the Experimental Setup

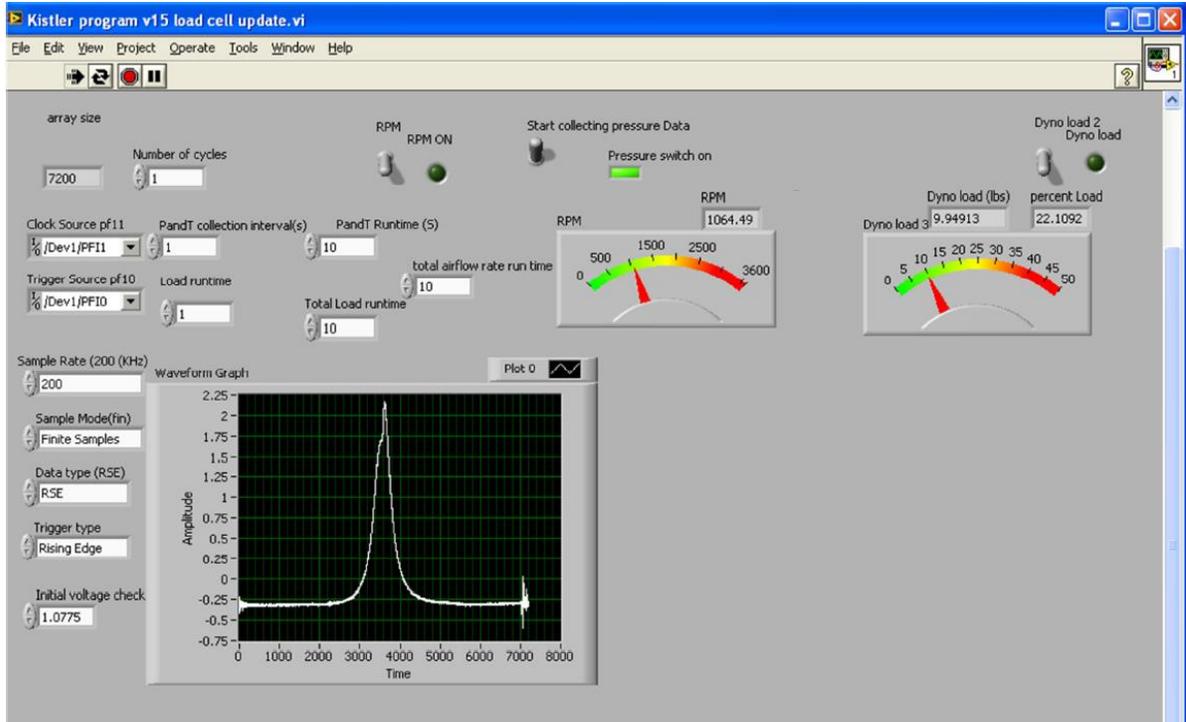


Figure 2.8 : Front Panel of the LabVIEW data acquisition program

## CHAPTER 3

### FUELS TESTED

#### 3.1. Diesel extracts of bio-oil mixed with diesel

The first fuel that was tested is a mixture of Wood Pyrolysis oil extracts and diesel. The oil used in this study was obtained by the pyrolysis of Loblolly pine wood and the oil was upgraded by a technique called liquid-liquid extraction. The aim was to extract mainly the phenolic compounds and to separate out water and organic acids. This technique is further discussed with the help of suitable references in the literature survey section of Chapter 4. The solvent used for this technique was diesel. The extraction was carried out four times resulting in a mixture consisting of 1% bio-oil extracts (by volume) in diesel. This mixture was further mixed with diesel in the ratio of 10%, 50% and 100% with diesel resulting in a final concentration of 0.1%, 0.5% and 1% diesel extracts of bio-oil in diesel. These fuels were named E180, E900 and E1800 where the numbers correspond to two times the concentration of diesel extracts of bio-oil in the mixture, in parts per million.

The entire process of pyrolysis and liquid-liquid extraction was carried out by Dr. Sunkyu Park's research group in the Department of Forest Biomaterials at North Carolina State University.

Physically, the diesel extracts of bio-oil in diesel, is a brown, viscous oil. It has a high concentration of phenolic compounds like guaiacol and eugenol. The concentrations of different organic components of the fuel is provided in Table 3.1 below.

Table 3.1: Concentrations of different organic compounds in the diesel extracts of bio-oil

<b>Component</b>	<b>Concentration (mg/L)</b>
o-Cresol-	233.3
p-Cresol	233.3
Guaiacol	483.3
2-Ethylphenol	16.7
3-Ethylphenol	75.0
4-Methylguaiacol	141.7
Catechol	141.7
3-Ethyl-5-methylphenol	100.0
4-Vinylguaiacol	116.7
4-Propenylphenol	33.3
Eugenol	41.7
Isoeugenol (cis)	33.3
Isoeugenol (trans)	133.3

### **3.2. Eugenol mixed with diesel**

One of the main phenolic compound in the diesel-extracts of bio-oil mixture highlighted above was eugenol. Eugenol is a hydrocarbon liquid which is mainly extracted from essential oils like clove oil, bay leaf etc. Studies have shown Eugenol to be a good diesel additive when used directly or when it was a major compound in other substances like clove oil.

These studies have been discussed in the literature survey section of Chapter 5.

In this study, eugenol was used as a fuel blend at slightly higher concentrations, as opposed to their use as additives with very low concentrations in diesel. The aim of such an exercise was to isolate the role eugenol played in the enhancement of diesel combustion and its feasibility to be used as a partial diesel fuel replacement. Although eugenol is relatively expensive, if its role in combustion yields favorable results, further studies can be performed with other compounds with high eugenol concentrations. 99% pure eugenol was mixed with commercially available diesel. Three ratios by volume were tested, namely, E5 (5% v/v), E10 (10% v/v) and E20 (20% v/v). As before, commercially available diesel was used. Some of the properties of the eugenol used is given in Table 3.2.

Table 3.2: Properties of Eugenol

Chemical Name	Eugenol
Synonym	4-Allyl-2-methoxyphenol, 2-Methoxy-4-(2-propenyl)phenol, Eugenic acid
Molecular formula	C <sub>10</sub> H <sub>12</sub> O <sub>2</sub>
Molecular Weight	164.2 g/mol
Purity	99%
Appearance	Clear, light yellow, liquid
Density	1.067 g/cm <sup>3</sup>
Boiling Point	254 Celcius
Flash point	112 Celcius

## CHAPTER 4

### PERFORMANCE AND EMISSION TESTING OF DIESEL-EXTRACTS OF BIO-OIL MIXED WITH DIESEL

#### 4.1 Abstract

An experiment was conducted with the aim of testing the basic performance and emissions behavior of a bio-oil extract mixtures with diesel. The extracts were produced, first, by making bio-oil samples from the pyrolysis of Loblolly pine wood. This sample was then subjected to liquid-liquid extraction with diesel as a solvent. The diesel extracts of bio-oil are then further mixed with diesel in three volume ratios, yielding final concentrations of 0.1%, 0.5% and 1% of diesel extracts of bio-oil in diesel. These three mixtures are named E180, E900 and E1800 to indicate diesel extracts of bio-oil and the concentration of the extracts in the mixture. Diesel was used as a baseline fuel for comparison. The engine was operated at 2000 RPM and three load conditions were tested, namely, no load, 12.6 bar BMEP and 3.28 bar BMEP. Overall, the bio-oil extract mixtures exhibit a marginally lower indicated work output and consequently, a higher mechanical efficiency than diesel. The drop in work done varied from 2.5% to 9% depending on the load conditions. However, the fuel consumption of the mixtures is lower than diesel especially at low to moderate loads. There was not much effect observed, in this regard, with increasing the concentration of the extracts. The in-cylinder pressure data was observed to be practically the same for all the fuels tested. A key difference in the combustion characteristics was the longer ignition delay which was observed in the bio-oil extract mixtures. At no load, E900 showed the longest delay. At 1.26

bar BMEP and 3.27 bar BMEP, E180 and E 1800 had the longest delays, respectively. Encouraging results were observed with respect to the emissions part of this experiment wherein the HC and NO<sub>x</sub> emissions were significantly reduced with the use of these bio-oil extract mixtures. The CO<sub>2</sub> emissions remained comparable to those of diesel. In light of the observations made in this experiment, these mixtures hold potential to address the performance and emissions needs of today. E900 appears to perform well at moderate loads while E1800 is well suited for high loads. Further experimentation with slightly higher bio-oil extract concentrations and at wider load range is needed to further pursue this avenue. Also the effect of the major, individual phenolic components of these extracts can also be studied in isolation to further pin-point their role in the combustion characteristics of these fuels.

## **4.2 Literature Review**

A good alternative that addresses the issues of renewability, pollution, compatibility and performance is bio-mass. The use of bio-mass also favors the economy of agriculture based countries. Bio-mass already plays a role in the energy sector by contributing to 13% of the world's primary energy consumption [5]. Bio-mass based fuels, which are called bio-fuels, are already being encouraged by the government in the form of increased tax benefits and other credits [8]. This has acted as an impetus to further research into these fuels. Bio-mass can be converted to utilizable forms of fuel by anaerobic digestion, hydrolysis, biophotolysis, pyrolysis, liquefaction, dry combustion, gasification, and solvent extraction. Of

these techniques, pyrolysis is the most promising. Pyrolysis is a process where the cellulose, hemicellulose, and lignin of biomass is decomposed into solids, gases, and liquid products in a high-temperature anaerobic environment [9]. It usually yields solid, liquid and gaseous products. Pyrolysis holds the advantage of high conversion efficiency, negligible waste, low pressure operation and independent feedstock. With the choice of different types of bio-mass available, the bio-oil obtained from wood, and hence called Wood Pyrolysis Oil (WPO) is being explored in this present study. Wood pyrolysis is characterized by high density and viscosity and has the tendency to form solid precipitates which can cause blockage in the fuel injection systems of engines. Also, having a low pH value, it is acidic and causes corrosion after long term operation. For these reasons, bio-oil cannot be used directly in engines without certain modifications. This is made worse by a high oxygen content and low calorific value. Such an attempt was made by [10] wherein modifications were made to the engine. Stainless steel mesh filters were used to capture particles in addition to pre-filtering with a separate pressurized filtration rig. The fuel injector return was diverted to a separate reservoir as build-up of particulates was expected to happen in the hot injector body. Also the fuel supply system was modified to include seamless transition between pure bio-oil and diesel with a transition of nitrate-enriched ethanol to flush the system to prevent residue. In addition to this, there was carbon build-up in the combustion chamber, exhaust valves and ports calling for disassembly of the cylinder head and cleaning of the components after every experiment. A similar attempt is carried out by [11] where despite the use of a ignition enhancer, similar results were observed with the use of direct bio-oil. In light of all this, with

the current technology, it is not practical to run pure bio-oil in an engine due to the major engine modifications required. This means that the bio-oil needs to be upgraded or altered in some way to allow its use in engines without physical modifications.

Bio-oil consists of different, complex organic compounds with different functional groups mixed together like alkenes, aromatics, phenols, guaiacols, furans, aldehydes, ketones and alcohols. The main hindrance to suitable upgradation of bio-oil is catalytic coking which is the formation of coke due to polycondensation polymerization reactions [12]. To cope with this problem, two main approaches are followed. The first is emulsification with diesel or bio-diesel along with a suitable emulsifier. A comprehensive review of bio-fuel emulsions is undertaken in [13]. Combustion efficiency improvement and a reduction in particulate matter and NO<sub>x</sub> emissions, were some of the general traits observed. Emulsification is a popular technique but emulsion stability is an issue. [14] have shown that the emulsion is stable for volume fraction less than 15%. In order to avoid this limitation and to explore other novel methods, another approach has been attempted.

This second method involves the extraction and separation of the oxygen containing functional groups from bio-oil and grouping them into separate phases. This is possible because the different functional groups have distinct polarities. This method is called solvent extraction or liquid-liquid extraction. A solvent is used to separate the bio-oil into two phases, a water-like phase and an oil-like phase. This methodology is not new in the study of bio-oils but innovation is manifested in the intelligent use of the solvents. Ionic liquids like water have been used to extract components of bio-oils like levoglucosan from bio-oil [15].

Both phase separation and extraction occurred simultaneously. The aim was to find the optimal amount of water for maximum levoglucosan extraction and it was found to be 1.3: 1, water to bio-oil ratio. An interesting study conducted by [16] used dichloromethane as a solvent for extraction, water as an anti-solvent to enhance phase split and also 1-butanol as a co-solvent to improve the solubility of the enhanced bio-oil in diesel. Promising results were obtained from the resulting mixture which had a high concentration of phenols and low sugar and water content. It also displayed good combustion characteristics. The mixture was studied for its combustion characteristics using thermogravimetry, differential scanning calorimetry and differential thermal gravity curves. The most combustion efficient fuel blend was found to be 55% modified bio-oil, 35% 1-butanol and 10% diesel. This method has even been used to extract bio-oil itself from *Jatropha* bio-mass by using a technique called co-solvent extraction where an ionic as well as hydrocarbon based solvents were used together [17]. The aim was to use this bio-oil as possible animal feed and so it was also desirable to remove toxic phorbol esters from the bio-mass. Methanol was mixed with varying concentration of [C2mim] MeSO<sub>4</sub> or [C2mim] Ac. It was found that an optimum solution of 30% [C2mim] MeSO<sub>4</sub> and 70% methanol completely extracted and separated the bio-oil and removed 99% of the phorbol esters. Another study used organic solvents like hexane, petroleum ether and chloroform. As before, water was used to separate the bio-oil (obtained from the pyrolysis of Douglas fir pellets) into a water-like phase. This was then mixed with the three different organic solvents in different volume ratios for extraction of mainly phenolic compounds and the removal of sugars and water. Hexane performed poorly in

comparison to chloroform with a low extraction of phenolics as well as guaiacols [12]. An optimum volume ratio of 1:1 of chloroform and bio-oil was found to give a maximum yield around 83 wt % guaiacols and 43 wt % phenols. This scheme resulted in about 66% of organics in the solvent phase. The use of organic solvents is common but the use of solvents which can be used as fuels in themselves is not well researched. The closest study in this regard is by [18] where extraction was carried out with water (phase separation) and octane or hexadecane (extraction), where octane and hexadecane molecules were representative of gasoline and diesel respectively. The aqueous bio-oil obtained by mixing with water was then mixed with octane or hexane in a weight ratio of 1:4. Two schemes viz. sequential and combined extraction were tested. In the case of combined extraction, both octane and hexadecane showed similar concentration of phenolics. While sequential extraction was preferred for the extraction of acetic acid without the organic solvents partitioning into the aqueous phase. In the current experiment, diesel was used a solvent thereby obtaining diesel extracted bio-oil and diesel extracts. The extraction was carried out four times in a multi-stage extraction process. It has been shown that multi-stage extraction is 1.5 to 3 times more efficient than single stage extraction for most components and can meet the demands of industrial level production [19]. The bio-oil used in the present study was obtained by the fast pyrolysis of clean pine wood. The diesel extracts of bio-oil and diesel are mixed and the resulting mixture is used as a fuel. It was observed that the diesel extracts i.e., the solvent phase showed a high concentration of phenolic compounds like guaiacol and eugenols. A

brief flowchart is shown in Figure 4.1 that explains the process of producing the diesel extracts of bio-oil mixture.

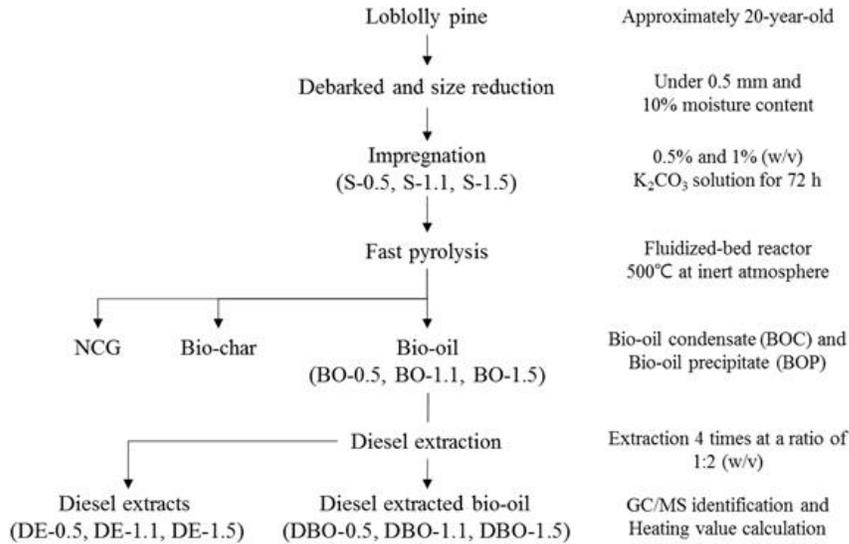


Figure 4.1: Flowchart of diesel extracts of bio-oil production

Testing of fuels in diesel engines can be carried out in several ways. The aim of any such testing procedure is to mimic real-life operations in terms of speed, load and duration. In the case of automobile engines, rigorous, standardized testing cycles can be used. In the present case, the choice of engine and hence the method of testing is more general with the aim of understanding the general behavior of the fuel rather than its specific characteristic in an application. The experiment is approached in two halves. First is the performance testing where the work performed by the combustion of the fuel and its efficiency are tested. The second part looks at the effect it has on the environment in terms of pollution. This kind of

testing has been performed extensively but with different types of bio-oil fuels which had been extracted from different sources through a variety of processes. In [20], Coffee Bean Residual Pyrolysis oil was emulsified with diesel in different proportions and tested. Firstly, with higher bio-oil concentration, the ignition delay was increased. This can be attributed to the higher density and viscosity of the bio-oil. Consequently, the peak pressure in the cylinder slightly increased as there was more time for proper mixing of the charge. Also for a given rotational speed, the indicated thermal efficiency decreased with higher bio-oil concentration, when compared to diesel and this difference was even more exaggerated at very high and very low speeds. So the use of bio-oil was suggested for intermediate rotational speeds of about 2000 rpm. It was also observed that increased bio-oil concentration reduced the NO<sub>x</sub> concentration but in some cases increases the smoke density, which can be attributed to the inferior quality of combustion due to higher water content, the presence of unwanted sulphur and overall inefficient combustion. A better understanding of the performance of bio-oil can be sought by comparing it directly with diesel. This is done in [21] where three bio-oils are emulsified with diesel. They were obtained from Prosopis Juliflora seeds, Coconut shells and Kiker seeds and these were compared with a baseline fuel of diesel. The Specific Fuel Consumption was higher for the bio-oil mixtures than compared to diesel. This was again attributed to higher viscosity and density resulting in inferior quality of combustion. The Brake Thermal Efficiency for all the fuels were nearly the same, including diesel, with a marginal decrease for the bio-oil mixtures as was expected from the rise in SFC. The slow burning nature of bio-oils seemed to make the bio-oils run hotter, as

was observed with the slightly higher exhaust temperature as well. As before the ignition delay was also extended for the bio-oils, and the authors cited the lower combustion chamber temperature due to the presence of water as the reason, thereby reducing the charge temperature. In this experiment, the peak pressure for the bio-oils was slightly lower than that of diesel. A similar trend was observed for the heat release rate also. Interesting observations were made with respect to the smoke emitted from the engine. The bio-oil mixtures emitted less smoke at all loads when compared to diesel. This behavior appeared to be more conclusive than the results published by [20]. The reasoning for this was thought to be breaking up of the large droplets (formed due to higher density and viscosity) by the micro-explosions caused by the heating of the water in the oils. This was termed as secondary atomization.  $\text{NO}_x$  output was also reduced in the case of the bio-oil emulsions. Hydrocarbon concentration, on the other hand, increased for all load conditions due to flame quenching caused by the high latent heat of vaporization of the water present in the case of bio-oil. This is also exacerbated by the slow combustion characteristics shown by these oils. As expected, the poor combustion characteristics of bio-oil caused higher CO concentrations in the exhaust. In [22], bio-oil obtained from the fast pyrolysis of lignocellulosic bio-mass was emulsified with diesel in a mass ratio of 3:7 and tested in a diesel engine. This emulsion showed a higher BSFC than diesel and had a slightly higher peak cylinder pressure. Uniquely, the heat release rate curve showed two peaks corresponding to the separate combustion of WPO and diesel and these peaks were attributed to micro-explosions occurring in the cylinder when the water in the fuel is suddenly vaporized. The HC levels

increased and was attributed to low cetane number and high ignition delay. Also increased levels of CO were observed due to incomplete combustion. NO<sub>x</sub> levels were relatively lower due to the emulsions high water content. Due to the presence of oxygen in these fuels and due to the micro-explosions, the soot emitted from their combustion was observed to be lower than that emitted by diesel. However a reversal in these trends were observed at load beyond 0.3-0.4 MPa.

In the current study, the bio-oil mixture obtained from liquid-liquid extraction using diesel was tested to compare both its performance and emissions characteristics with diesel. Although a few attempts have been made in the synthesis of bio-oil mixtures using this method, a comprehensive engine test of the same has not been carried out. Further, since the solvent used is in itself a fuel, favorable results are expected. This study attempts to verify this by performing a performance and emissions test on these fuels.

### **4.3 Experimental Procedure**

For this experiment, the fuels were obtained from the Department of Forest Bio-Materials. A sample of 1% of diesel extracts of Bio-oil in diesel was further mixed with diesel in three ratios i.e., 10% by volume, 50% by volume and 100% resulting in a final concentration of 0.1% in diesel, 0.5% in diesel and 1% in diesel. These three mixtures are named as E180, E900 and E1800 which stands for twice the concentration of diesel extracts of bio-oil in the mixture, expressed in parts per million. These

three samples were tested at three load conditions which corresponded to a brake mean effective pressure of 0, 1.26 and 3.26 bar respectively. The speed chosen for this test was 2000 RPM. These load and speed conditions were arrived at with the aim of studying the behavior of the fuel over a wide range of load conditions while keeping in mind the amount of fuel sample available for testing.

The engine was warmed up and set at the correct test conditions using diesel. The diesel was then removed and replaced by the fuel to be tested. The engine was allowed to run for an additional 10 minutes to burn the residual diesel in the fuel supply system and for the engine to settle down on the new fuel before data was collected.

Once the test conditions of speed and load were verified by using the sensors, both performance and emissions data was collected. In-cylinder pressure data was averaged and smoothed over 25 random cycles. Three trials were taken and averaged for all other readings.

## **4.4 Results and Discussion**

### **4.4.1 Performance**

The fundamental performance measure of a fuel combusting in an engine is the work that is produced. The indicated work is the work obtained by integrating over the Pressure vs Volume curve. The indicated work discussed here is net indicated work which refers to the work delivered to the piston over the entire four-strokes of the engine and the results are presented in Figure 4.2. Firstly, as the load increases, the indicated work done increases as expected. This is because the engine will have to perform more work to overcome the increase in the load while its speed remains constant at 2000 rpm. Observing the indicated

work produced by the bio-oil mixtures, it is clear that it is lower when compared to diesel. There does not seem to be a direct correlation between the concentrations of the bio-oil extracts in diesel, with the work that is produced. At no load condition, there is a difference of about 7.5 to 9% between the diesel extracts of bio-oil mixtures and diesel, with the maximum work seen at E900 with diesel. At 1.26 bar BMEP, the drop is about 2.5% between pure diesel and the bio-oil extract mixture but with an exception for E900 which shows an increase of 2.38% when compared with pure diesel. A similar pattern is seen at the higher load of 3.28 bar BMEP where, the bio-oil extract mixtures with diesel show a drop of about 3% when compared to pure diesel. However, an exception is observed at E180, where the drop is marginal at 0.3%. A correlation between the indicated work and the ignition delay experienced during the combustion of the fuels can be determined. From Figure 4.5 we see that the ignition delays for the bio-oil mixtures are higher than that for diesel. This is expected since the bio-oil mixture is more viscous and denser than pure diesel. The higher ignition delay means the combustion occurs just after the Top Dead Centre, resulting in less positive work output. The marginal drop at 3.28 bar BMEP for E180 can be attributed to the identical ignition delays between the bio-oil mixture and pure diesel, in which case, a very similar work output can be expected. The chemical kinetics of the mixture can also play a role in the longer ignition delay and can contribute towards the slow burning characteristics of the bio-oil extract mixtures.

The mechanical efficiency is the ratio of the brake power delivered by the engine to the indicated power. By design, the brake power is kept constant at a particular load condition.

Following the trend mentioned for indicated work, the mechanical efficiency increases with increasing load (Figure 4.5). Also for a given load, the mechanical efficiency is higher for the bio-oil mixtures owing to the lower indicated work output given by those fuels. At 1.26 bar BMEP, the highest efficiency is observed by E1800 at 60.25% and at 3.28 bar BMEP, the highest efficiency is observed at 81.4% by both E900 and E1800. As the variations in the mechanical efficiency is solely due to the variations in the indicated work, the influence of ignition delay on the indicated work also explains the trends observed for the mechanical efficiency.

The Brake Specific Fuel Consumption (BSFC) is the ratio of the fuel consumed by the engine and the brake power it produced (Figure 4.4). The BSFC decreases with increasing load as the brake work increases and dominates over the increase in the fuel consumption. At 1.26 bar BMEP, the lowest BSFC is observed by E180 and E900 with a value of 0.46654 kg/kWh and closely followed by E1800 which had a BSFC of 0.4734 kg/kWh. Although these values are much lower than the value for diesel which was 0.5145 kg/kWh, it is clear that the change in concentration of bio-oil mixture has a minor effect on the BSFC. At 3.28 bar BMEP, the BSFC is for E180 and E900 are slightly higher than diesel while E1800 has the same BSFC. The lower fuel consumption exhibited by the bio-oil extract mixtures at 1.26 bar BMEP, can be due to better calorific value of the mixture. A thermo-chemical analysis of these mixtures is required to gain more knowledge about this.

#### 4.4.2 In-Cylinder Phenomena

The in-cylinder pressure is plotted as a function of crank angle and is analyzed on the basis of both varying load and for different fuels. For the four fuels under consideration the peak pressure increases with increasing load and also the rate of pressure increase also increases as the load increases, which can be seen in Figures 4.6a-b and 4.7a-b. This is in agreement with the smaller ignition delays observed in Figure 4.5. In Figures 4.8 a-c, it is observed that at no load, the peak pressure obtained by the diesel extracts of bio-oil mixtures is slightly lower than that obtained by pure diesel. E1800 has the highest peak pressure of 5.235 MPa, among the bio-oil extract mixtures and the pressure peak decreases as the bio-oil extract concentration decreases. It is also observed that there is no significant change in the rate of pressure rise between the fuels as the curves for all the fuels in the pre-mixed combustion stage are parallel to each other. At 1.26 bar BMEP, the peak pressures for all the fuels are nearly the same with an exception with E900 which has a slightly higher peak pressure than diesel, 5.907 MPa and E1800 has the lowest peak pressure of 5.81 MPa. At 3.28 bar BMEP load conditions, the same trend of lower peak pressure is observed for the bio-oil mixtures and again E1800 has the lowest peak pressure of 6.58 MPa but is only marginally lower than E900 and E180. This trend of the bio-oil extract mixtures having lower peak pressures despite having a longer ignition delay can be explained by their higher viscosity and density. This also explains the observation that E1800 has the lowest peak pressure under loaded conditions as E1800 will be the most viscous and dense of the lot. The ignition delay could also push the point of peak pressure past TDC, wherein the instantaneous volume of the

chamber is more and hence the recorded pressure by the same amount of gas is less. This effect is clearly seen at 1.26 bar and 3.28 bar BMEP.

The heat release rate plots give us information on the ignition delay experienced during combustion and also shed light on the behavior of the combustion during the pre-mixed and diffusion stages. From Figures 4.9a-b and 4.10a-b, it is seen that for all the fuels tested, as the load increases, the peak heat release rate increases as more work is done by the engine at higher loads and hence the rate at which heat is released should increase to provide more work at the same operating speed. However Figure 4.11a-c show that for a given load, the difference in the peak heat release rate is minor and negligible. Variations in the slope and lateral deviation of the heat release curves is visible which points towards the variations in ignition delay. As expected from the smaller ignition delay, the peak heat release rate occurs earlier, away from TDC. The ignition delay is calculated from the heat release data and is defined as the number of crank angles from the start of combustion (which in this case is 343 degrees from Bottom Dead Centre) to the point where the heat release rate becomes positive. This data is presented in Figure 4.5. The ignition delay is lower for all fuels when the load increases. At no load the mean delay is about 11 degrees whereas it drops to 10.6 and 10.25 degrees at 1.26 bar and 3.28 bar BMEP, respectively. This is can be explained in terms of air-fuel ratio which are expected to be richer at higher loads, resulting in hotter combustion temperatures which speed up the initial lag in the ignition of the charge resulting in lower delay. At no load, the bio-oil extract mixtures exhibit higher ignition delays, with the highest

being exhibited by E900 with a delay of 11.2 degrees. At 1.26 bar and 3.28 bar BMEP, the same trend of higher ignition delay is observed but the highest is exhibited by E180 in the former and E1800 in the latter load condition, with delays of 10.8 and 10.6 respectively. Also the E180 showed the same ignition delay as pure diesel at 3.28 bar BMEP. This trend of increased delay in the case of the bio-oil extract mixtures can be caused by the increased density of these fuels. As before, the chemical kinetics can also play a role. The heat release curves of the diesel extract mixtures seem to indicate that at higher loads, they exhibit slow burning characteristics and are comparable to diesel at lower loads and this tendency is manifested more as the concentration increases.

The cumulative heat release for the fuels at a given load are shown in Figures 4.12a-b and 4.13a-b and Figure 4.14a-c show the cumulative heat release for all the fuels at a given load. At all load conditions, the cumulative heat release of the bio-oil mixtures are lower than that of pure diesel with an anomaly observed for E900 at 1.28 bar BMEP, where the cumulative heat release is higher than that of diesel. Comparing the heat release for the bio-oil extract mixtures, a clear pattern is not apparent but the values are very similar to each other and lie within 3 to 5% of each other. This might indicate that the concentration of the bio-oil mixture does not have a significant effect on the overall amount of heat that is released during the combustion process but overall, these mixtures release lesser heat than diesel.

#### 4.4.3 Emissions

HC concentration is a good indication of the quality of combustion taking place in the engine. From Figure 4.15 we see that the HC concentration reduces with the increase in bio-oil extract concentration. At no load, E180 has almost no effect on the HC concentration but at all other load conditions and concentrations the effect is very apparent, even for E180. The decrease in HC can be attributed to the increase in oxygen content in the fuel which provides more oxygen during the combustion process resulting in cleaner combustion. It is observed that the lowest HC concentrations are observed for 1.26 bar BMEP. This is observed for the highest extract concentration namely, E1800. At 3.26 bar BMEP, the HC levels are higher possibly due to the domination of the effect that a richer fuel-air mixture has on the combustion characteristics. A richer mixture will result in more incomplete combustion which offsets the effect of increased oxygen.

Carbon monoxide is formed by the incomplete combustion of carbon. From Figure 4.16, we see that CO concentration decreases drastically at higher loads. At no load, the bio-oil extract mixtures emit about 0.103% of CO whereas at 3.28 bar BMEP, diesel and E180 emit no CO while E900 and E1800 exhibit trace amounts. This is expected as, at higher loads, the combustion chamber is much warmer and hence better mixing of the fuel-air mixture takes place, resulting in cleaner combustion. The bio-oil extract mixtures seem to have a slightly higher CO concentration than diesel but show slight variations based on the load conditions. The higher CO concentration can be explained by the higher density of the bio-oil mixtures.

They might not break up into smaller particles thereby causing ineffective combustion. This is despite the longer ignition delays and increased oxygen content in these mixtures. When the engine is not loaded, the difference in concentration of the mixtures has no effect on the CO emitted. However at 1.26 bar and 3.26 bar BMEP, E1800 has a slightly higher CO emission than E900.

Closely related to CO emissions is the Carbon dioxide (CO<sub>2</sub>) emissions. Following the cleaner combustion that takes place at higher loads, the carbon is oxidized in a clean or complete manner to form CO<sub>2</sub> and hence the CO<sub>2</sub> concentration increases with load as can be seen in Figure 4.17. Additional carbon will be available as more fuel is burnt to produce more work. The bio-oil extract mixtures show almost no variation when compared to diesel, in terms of the CO<sub>2</sub> emitted. At no load, the CO<sub>2</sub> for these mixtures is marginally higher than diesel, varying from 1.03% to 1.05%, as compared to 0.99% of diesel and at loaded conditions, they are even lower.

In Figure 4.19, the exhaust gas temperature of the engine is presented. The gas temperature is hotter as the load rises as more fuel is burnt and more heat is released. Comparing the bio-oil extract mixtures and diesel fuel, we see that the bio-oil mixtures run hotter than diesel with respect to the temperature of the exhaust gas they emit. There is not much difference between E180 and diesel but there is an increase in temperature at the other two concentrations. At 1.26 bar BMEP load condition, the maximum temperature is attained by E900 of 312.3° C

whereas diesel exhibited a temperature of 310° C. At 3.26 bar BMEP, E1800 has a higher exhaust gas temperature of 450.6° C while with diesel, a temperature of 425.3° C is observed. This increase of the temperature can be attributed to the stronger secondary combustion or diffusion combustion where more heat is released in the later part of the combustion. The increased ignition delay of the bio-oil mixtures also contributes towards this late heat release. This higher secondary combustion can be seen in Figure 4.10a-b and 4.11 a-b, show the heat release curves for the bio-oil mixtures are slightly higher than the curve for diesel. The observation that the temperature rise is not that significant at lower temperatures and in the case of E180, it is lower than diesel seems to indicate that there are more complex factors which influence exhaust temperature.

NO<sub>x</sub> emissions are generally formed in high temperature environments. At higher loads, it is expected that more NO<sub>x</sub> is emitted as the temperature of combustion is much higher as more fuel is being burnt and more energy is being released at higher loads. This is what is observed from Figure 4.20. However, the bio-oil extract mixtures, in comparison to diesel, emit slightly lower amount of NO<sub>x</sub>. The NO<sub>x</sub> levels at no load vary between 10.6 ppm for E1800 and 28.3 ppm for diesel while at 3.28 bar BMEP, it varies from 279.6 ppm for E900 and 301.6 ppm for E180. This can be due to higher oxygen and water content in the fuel which result in lowering the localized temperature in the combustion chamber thereby lowering the NO<sub>x</sub> formation. The delayed ignition also results in lower combustion temperature. However the trends seen in the heat release rate peaks do not reflect this cooling effect. This might suggest that other factors like the bonding of the nitrogen in the fuel can come into play.

## 4.5 Conclusion

An experiment was conducted to test the combustion characteristics of diesel extracts of bio-oil mixed with diesel in three volume ratios. The evaluation was on the basis of performance as well as emissions observed from the combustion of the fuel. Some of the important conclusions drawn from this experiment are shown below.

1. The indicated work produced by the bio-oil extract mixtures is slightly lower than that produced by diesel. At no load, this decrease is about 7.5% to 9% and at higher loads, the difference drops to about 2.4% to 3%. However exceptions were observed for E900 and E180 where the indicated work was marginally higher than diesel, at 1.26 bar BMEP and 3.28 bar BMEP respectively. Following this trend, the mechanical efficiency exhibited by the bio-oil extract mixtures is slightly higher than that of diesel since the brake work is constant by design and only the indicated work affects the mechanical efficiency.
2. An encouraging performance observation is the drop in BSFC observed for the bio-oil extract mixtures when compared to diesel. Nearly, a 9% drop is observed for the bio-oil mixtures at 1.26 bar BMEP. However, there was a slight increase in BSFC for E180 and E900. Overall, the fuel consumption was slightly lower than diesel.
3. Analysis of the in-cylinder pressure shows that the bio-oil extract mixtures exhibit a slightly lower peak cylinder pressure but the decrease is very slight and for practical purposes can be comparable to that of diesel. A contradiction is exhibited in the fact that the longer ignition delay, which is derived from the heat release rate data, points

towards a longer mixing period for the bio-oil extract mixtures which should result in a higher peak pressure. This apparent contradiction can possibly be explained by the high density and viscosity of the mixtures which result in poor atomization of the fuel thereby producing lower pressures and also by the possibility of pushing the point of maximum pressure past TDC, where the instantaneous volume is more.

4. A few encouraging results were observed for the emissions portion of the experiment, the most important of which was the reduced HC and NO<sub>x</sub> concentration which was exhibited by the bio-oil extract mixtures. Also the CO<sub>2</sub> concentration remained fairly the same as that of diesel with minor drop in the emission level at higher load. These are positive trends despite the higher exhaust temperature and the higher viscosity of these fuels in general and can be leveraged in future experimentation with different extract concentrations.
5. The performance aspects of this experiment show that the bio-oil extract mixtures tested are comparable to diesel in terms of the work output they produce and are in fact, superior in terms of fuel consumption at moderate loads. On the other hand, the emissions results further encourage the use of these mixtures, as key pollutants like HC and NO<sub>x</sub> emissions are reduced by their use. At low to moderate loads, E900 seems to be the best performing fuel and at higher loads, E1800 is more promising. Further experimentation with slightly higher concentrations at a wider load range can provide a more comprehensive picture of what concentration can be used for different

applications and these specific mixtures can be further studied for their feasibility of commercialization.

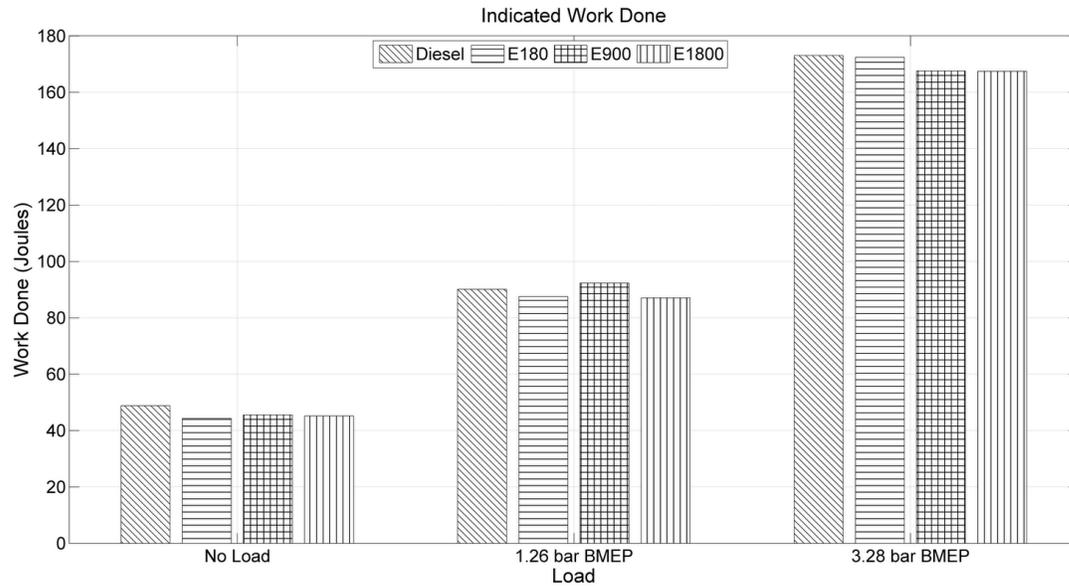


Figure 4.2: Indicated Work for all fuels at different BMEPs

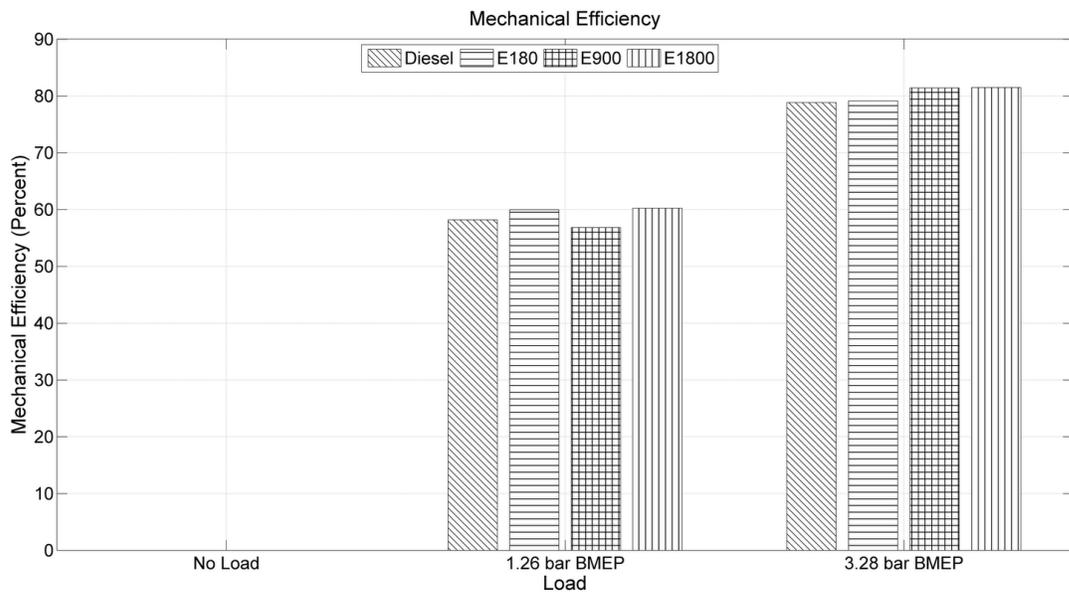


Figure 4.3: Mechanical Efficiency for all fuels at different Brake Mean Effective Pressures

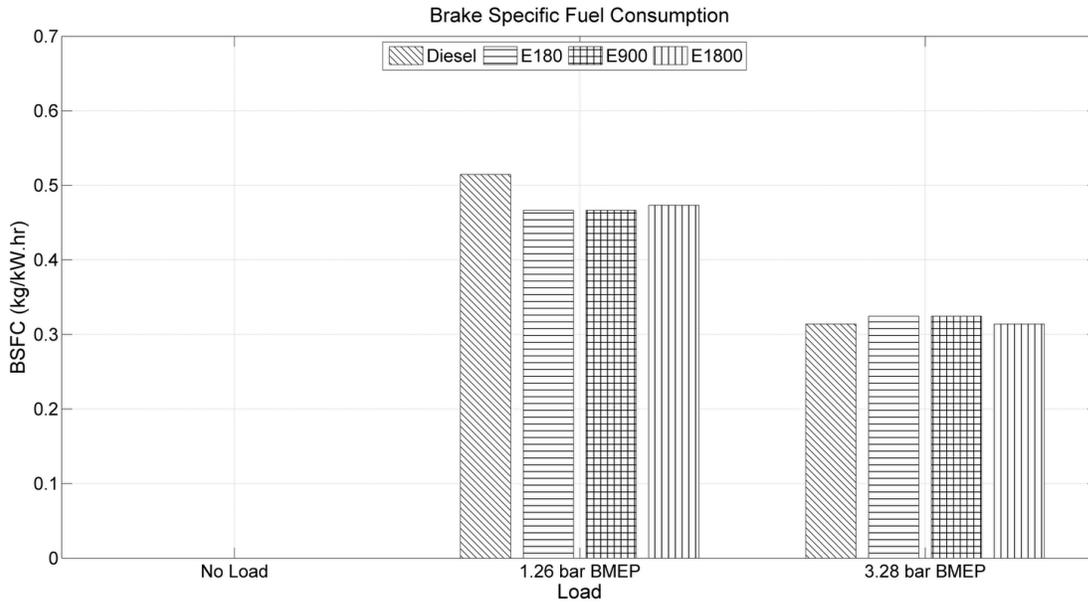


Figure 4.4: Brake Specific Fuel Consumption for all fuels at different BMEPs

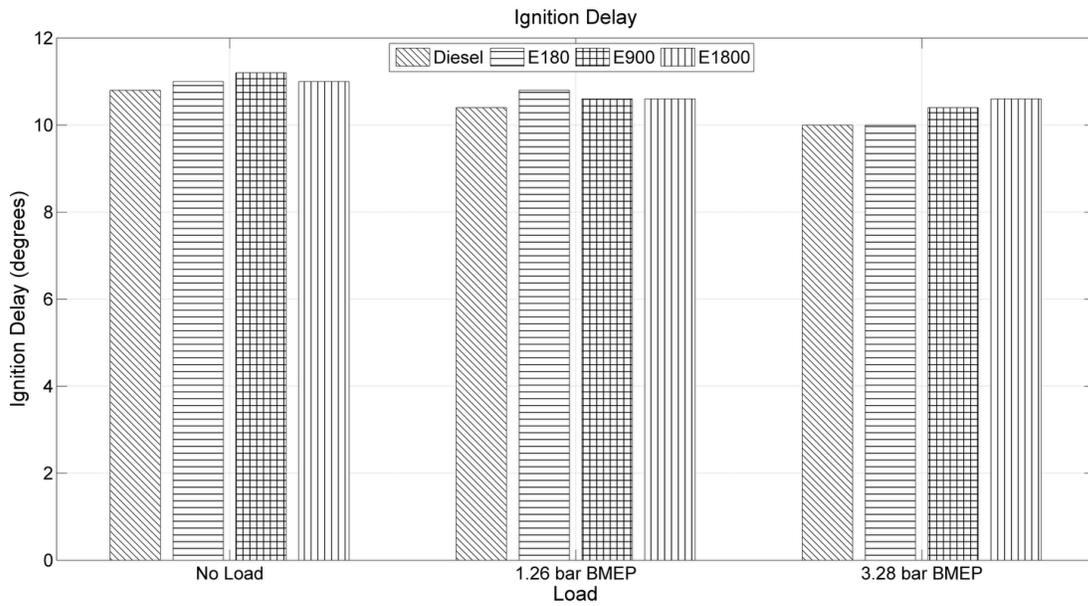


Figure 4.5: Ignition Delay for all fuels at different BMEPs

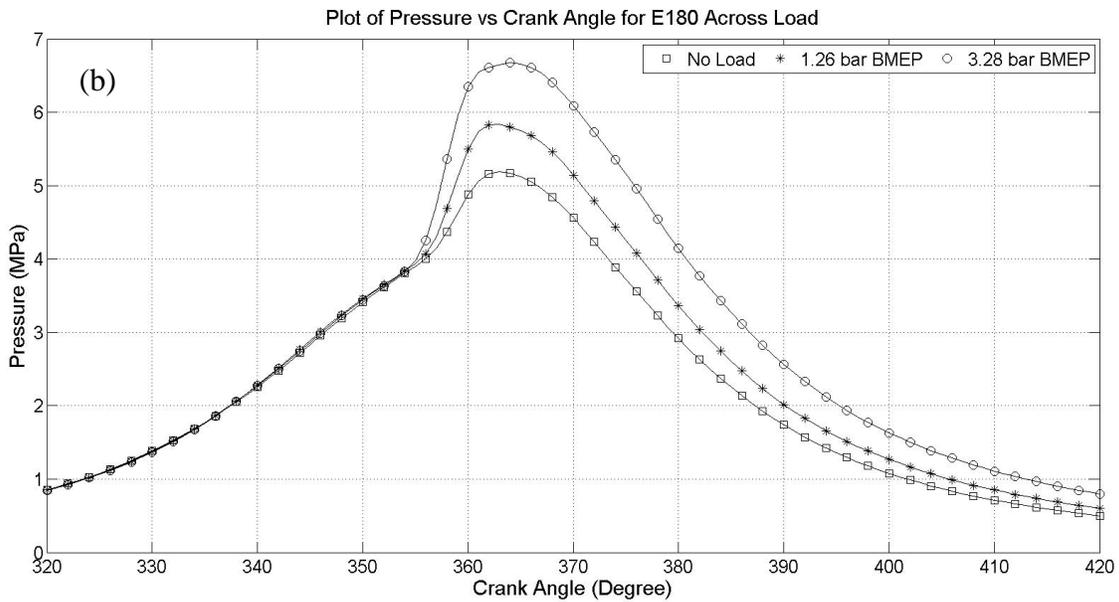
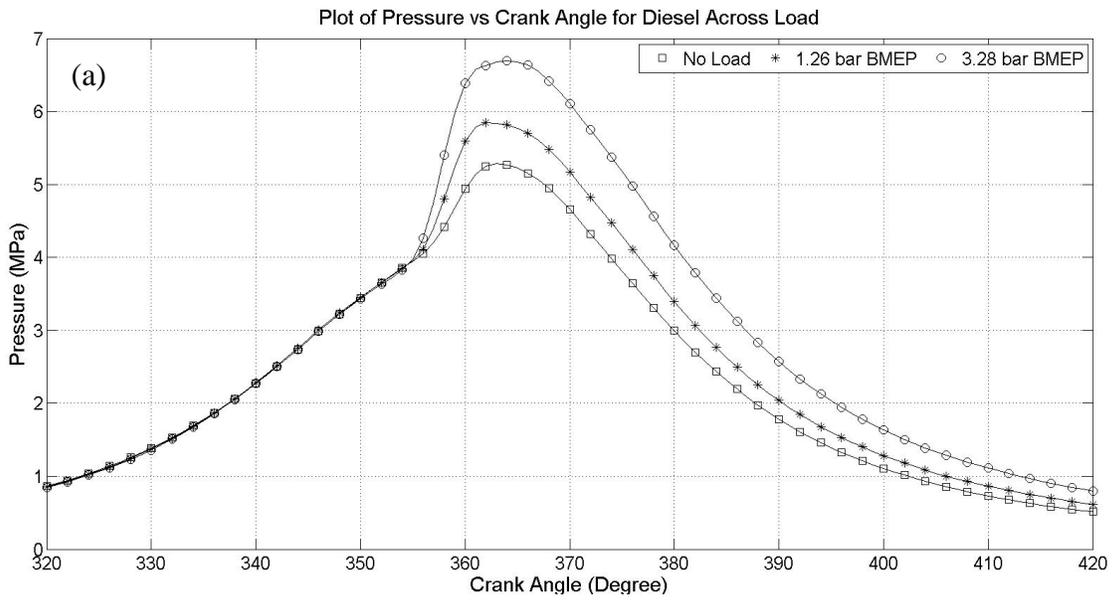


Figure 4.6: In-Cylinder pressure for (a) Diesel (b) E180 at different BMEPs

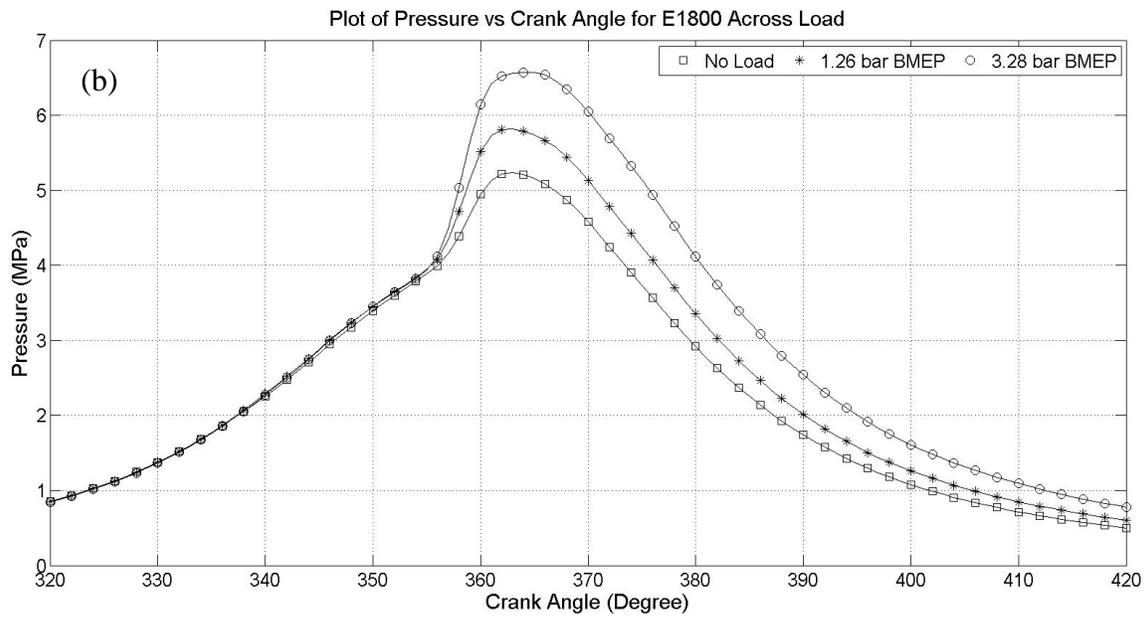
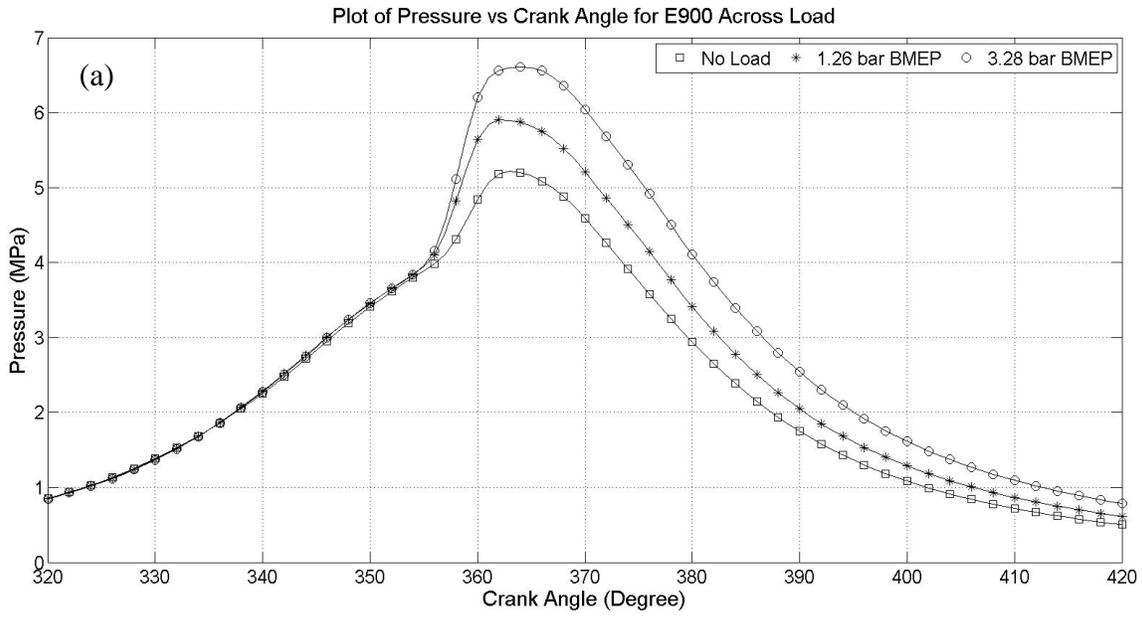


Figure 4.7: In-Cylinder pressure for (a) E900 (b) E1800 at different BMEPs

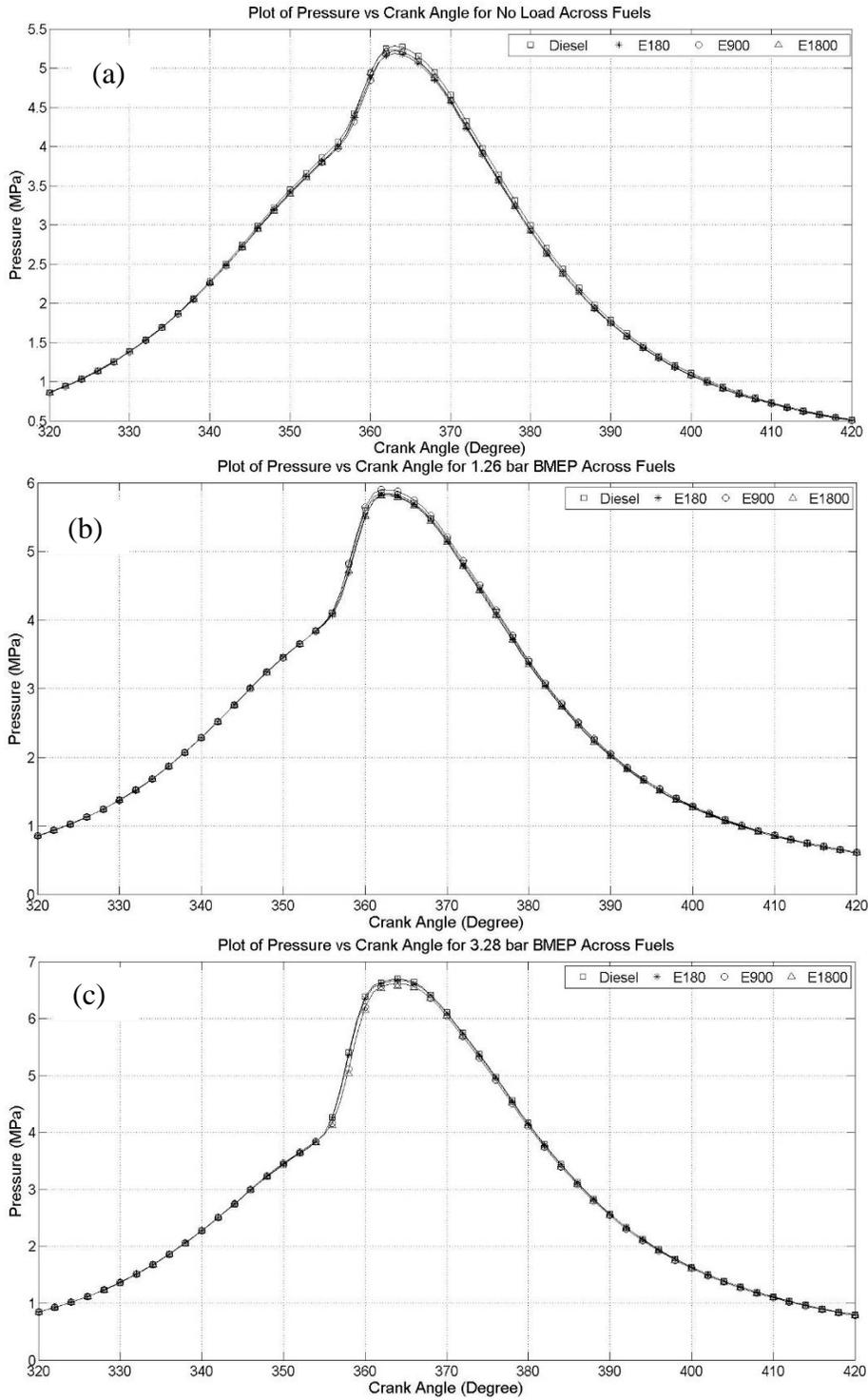


Figure 4.8: In-Cylinder pressure at (a) 0 bar (b) 1.26 bar (c) 3.28 bar BMEP for all the fuels

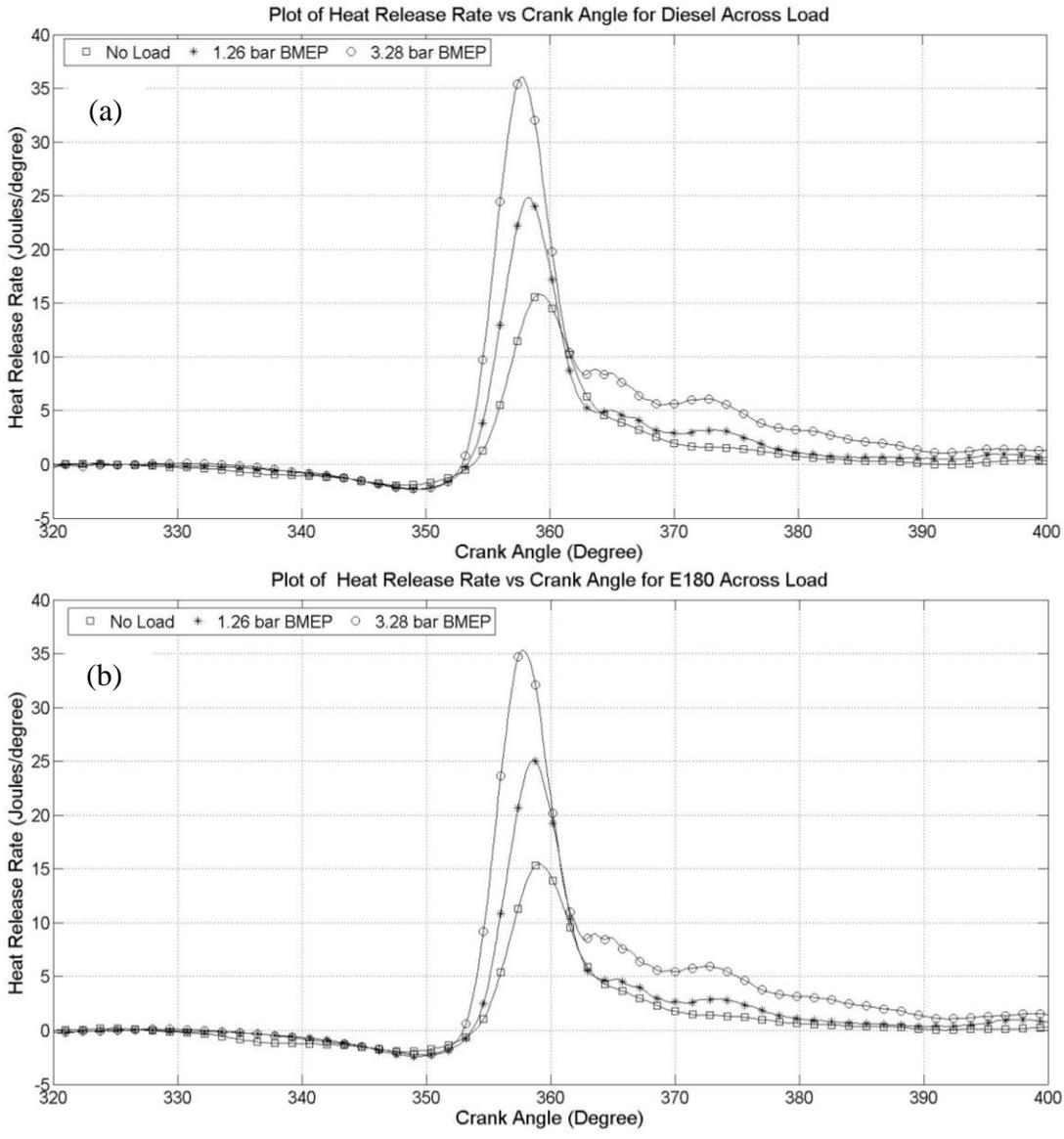


Figure 4.9: Heat release rate for (a) Diesel (b) E180 at different BMEPs

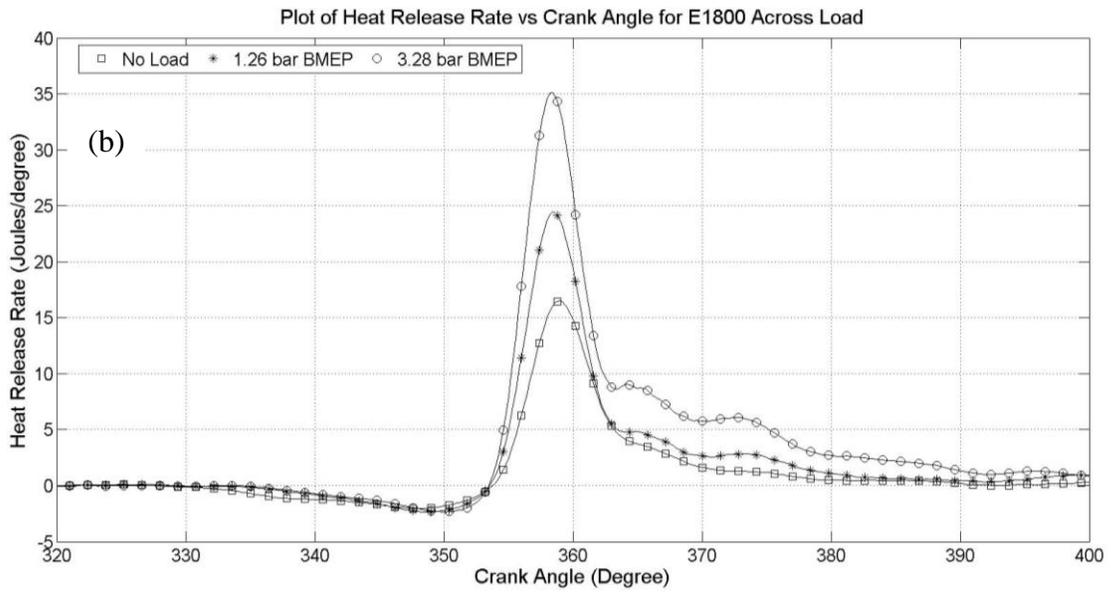
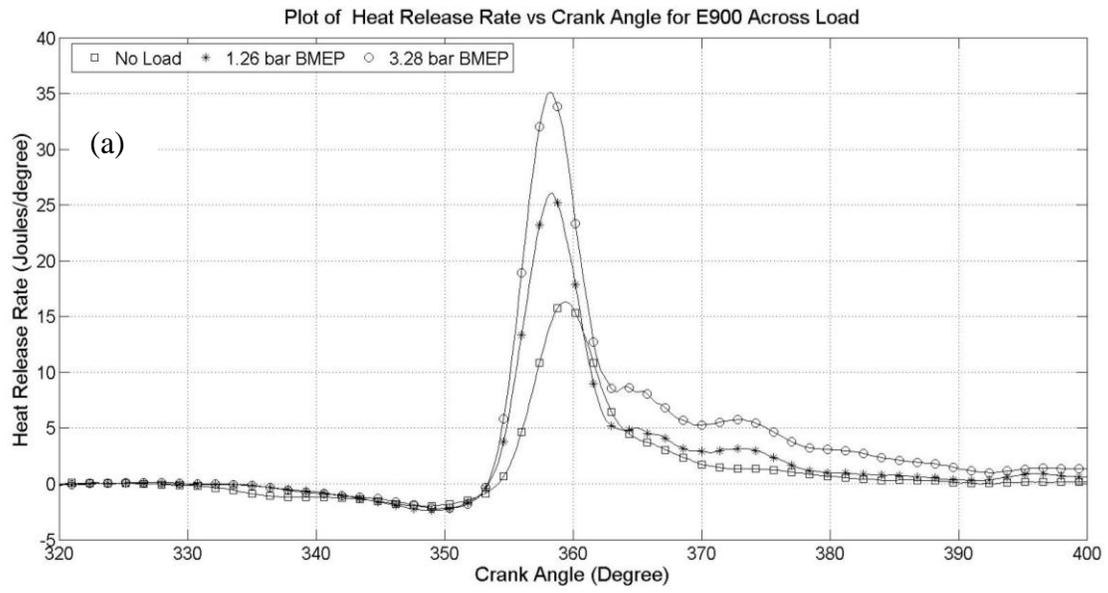


Figure 4.10: Heat release rate for (a) E900 (b) E1800 at different BMEPs

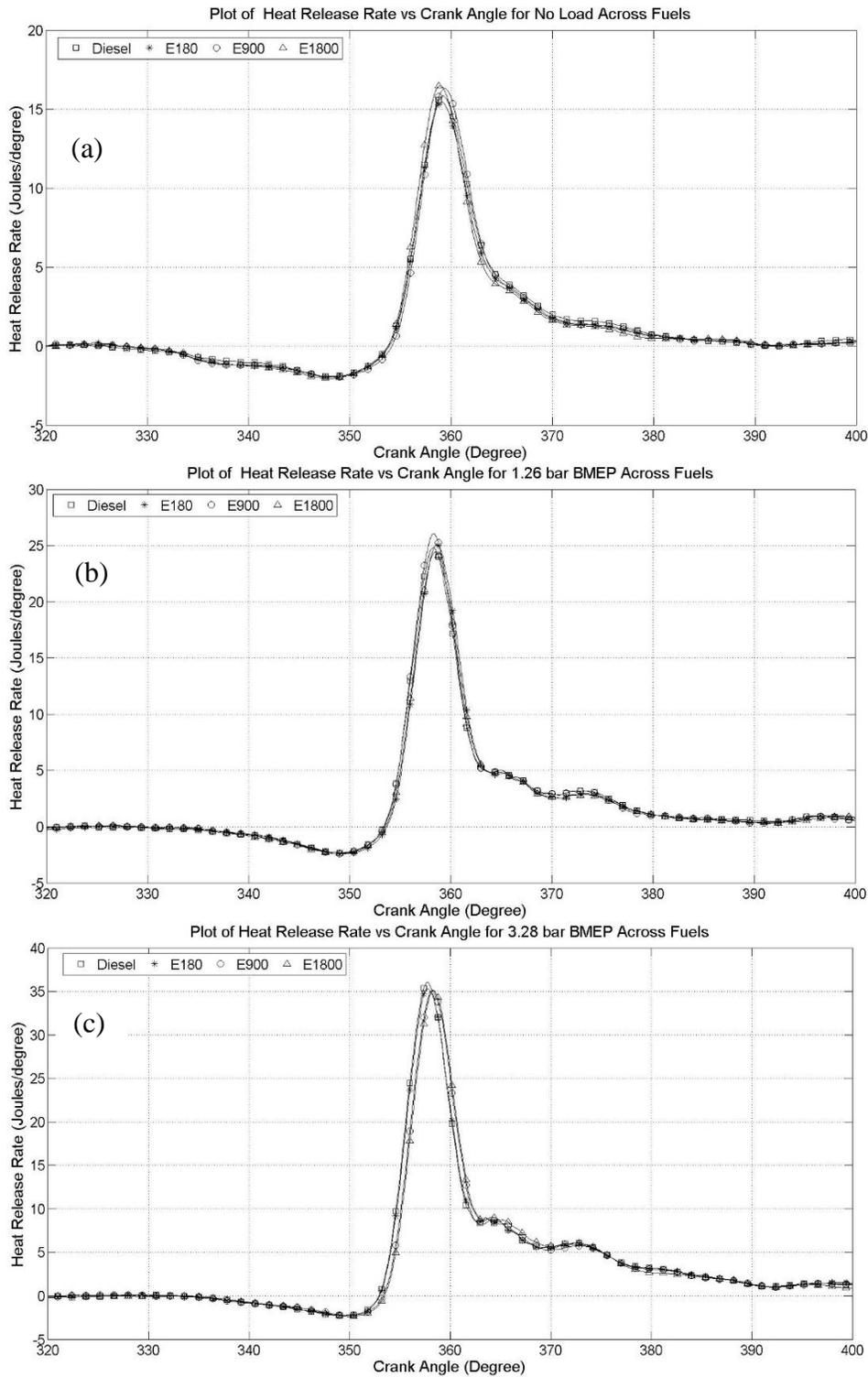


Figure 4.11: Heat release rate at (a) 0 bar (b) 1.26 bar (c) 3.28 bar BMEP for all fuels

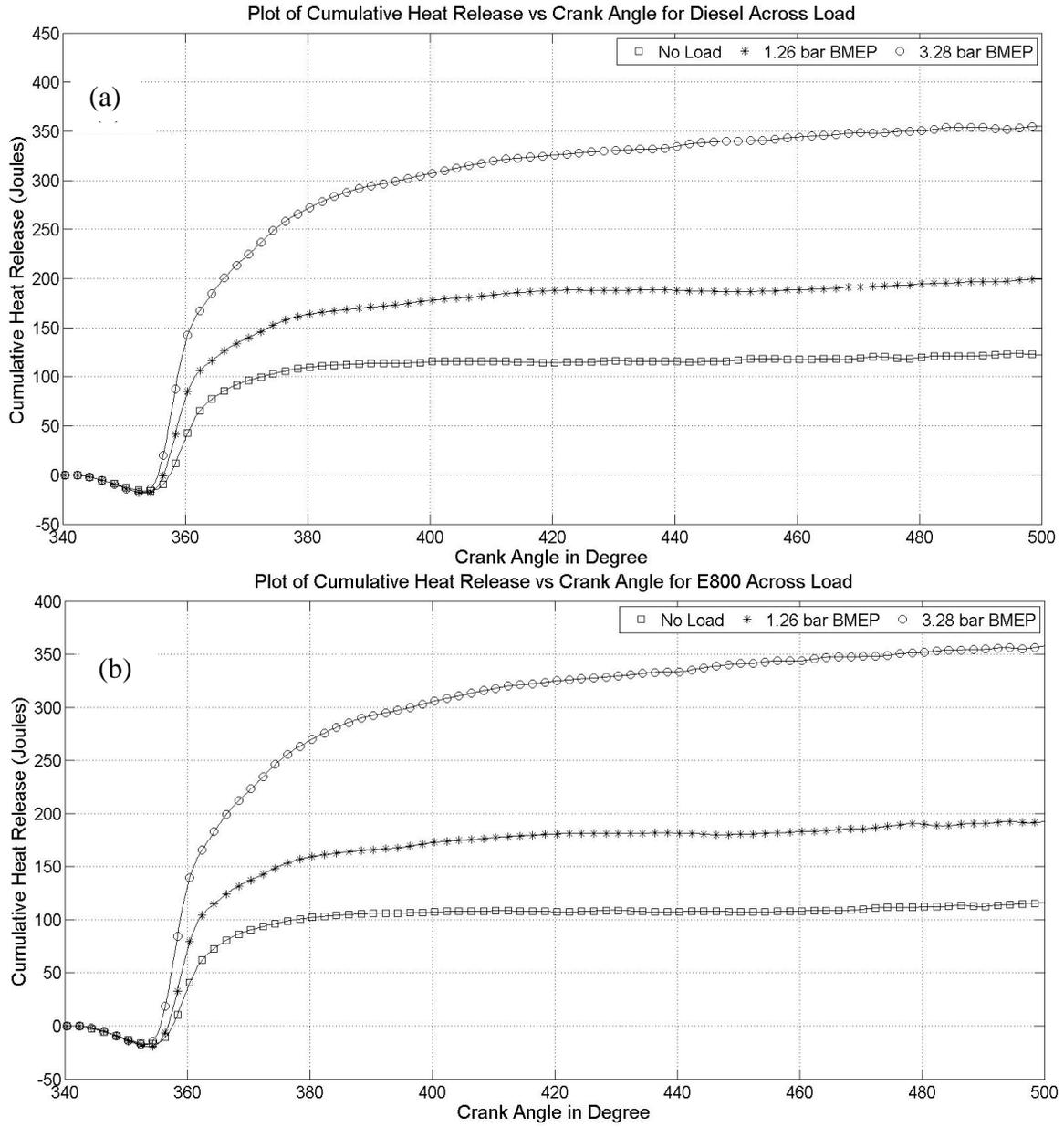


Figure 4.12: Cumulative heat release for (a) Diesel (b) E180 at different BMEPs

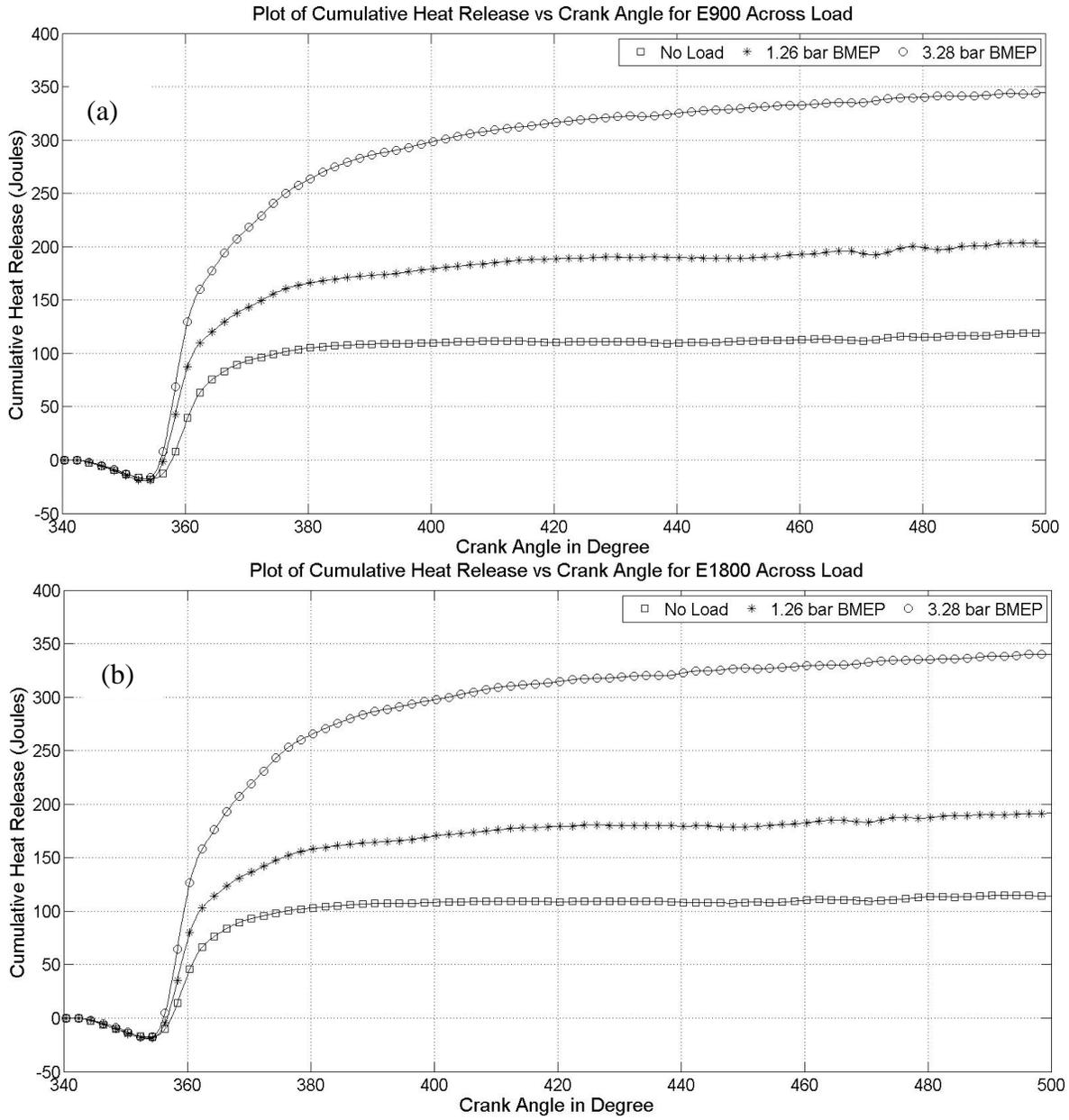


Figure 4.13: Cumulative heat release for (a) E900 (b) E1800 at different BMEPs

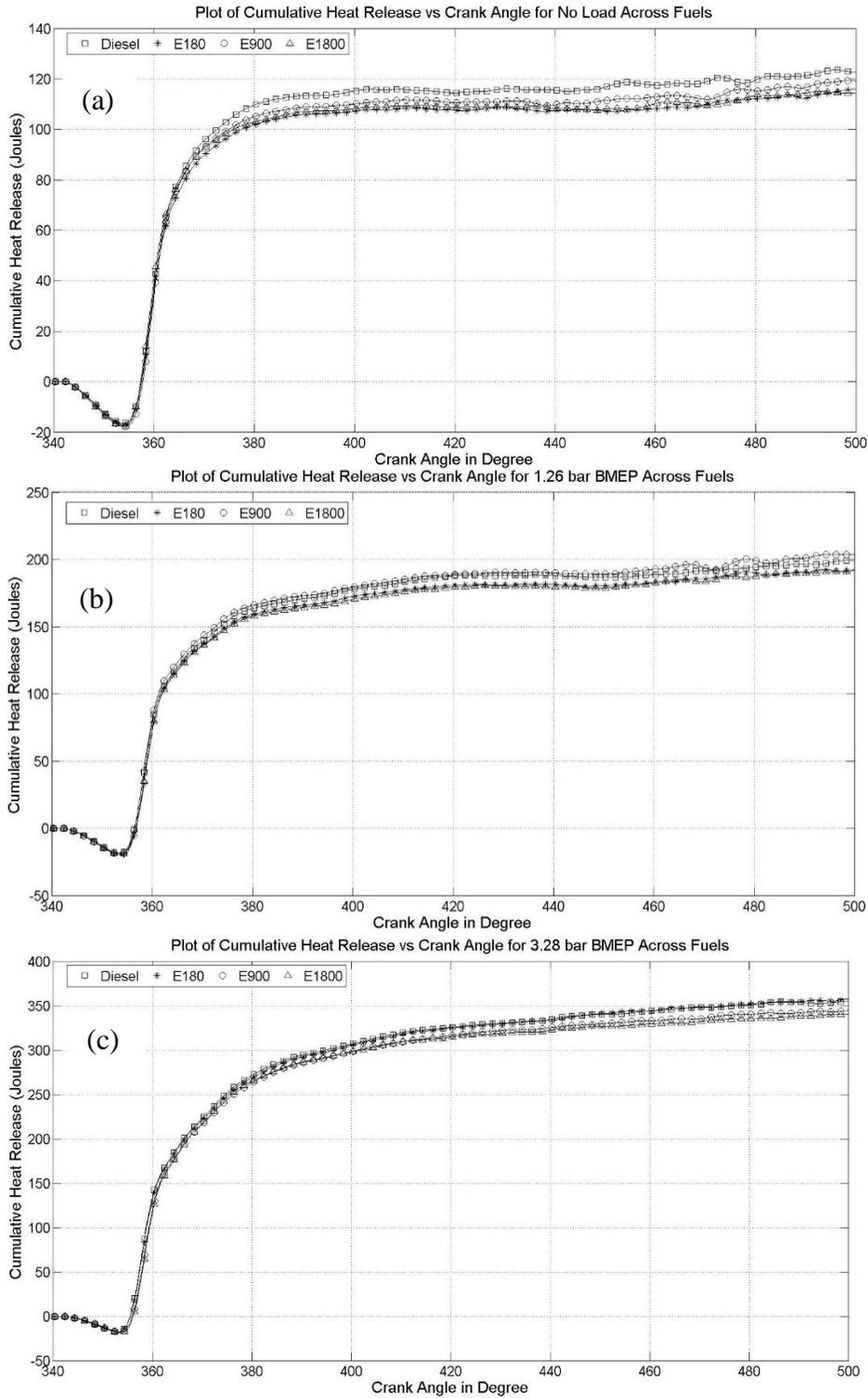


Figure 4.14: Cumulative heat release for (a) 0 bar (b) 1.26 bar (c) 3.28 bar BMEP for all fuels

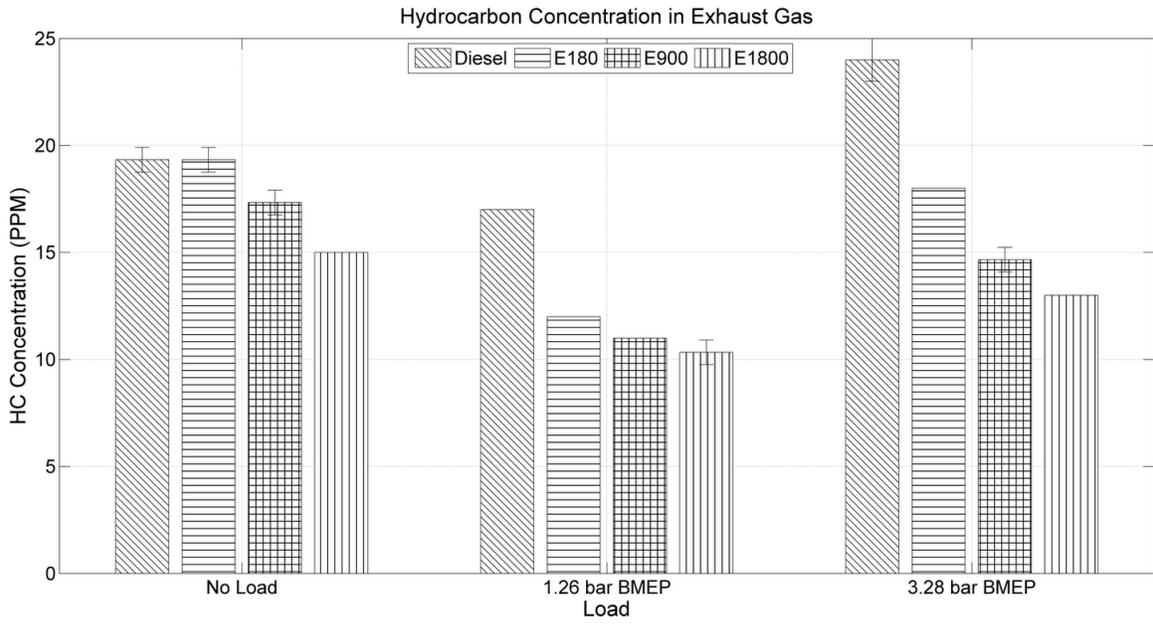


Figure 4.15: Hydrocarbon Emissions for all fuels across all loads

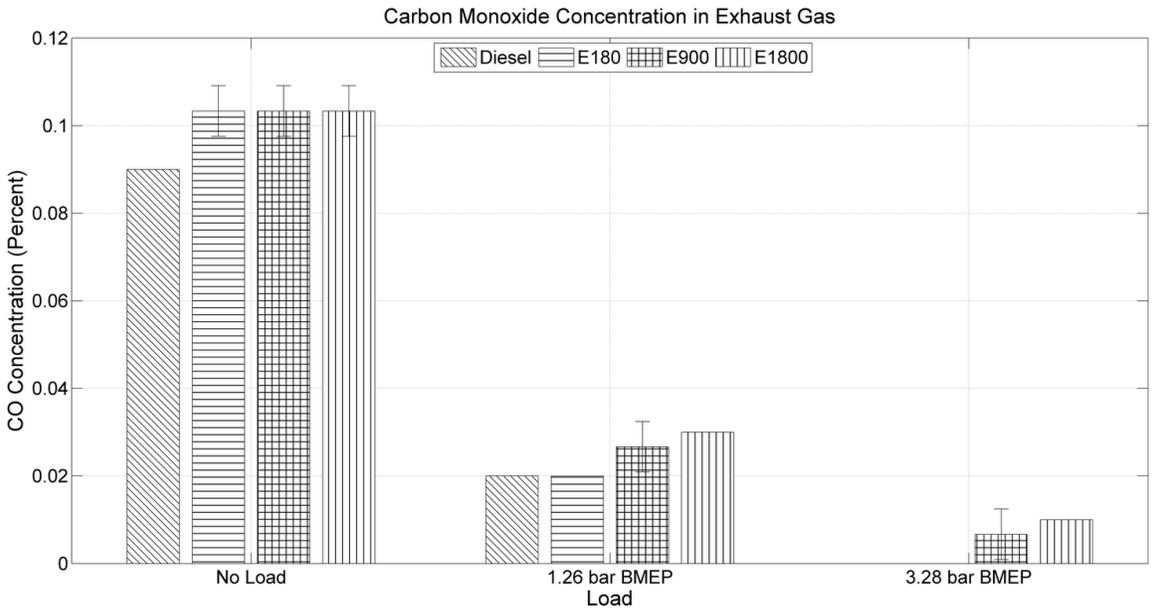


Figure 4.16: Carbon Monoxide Emissions for all fuels across all loads

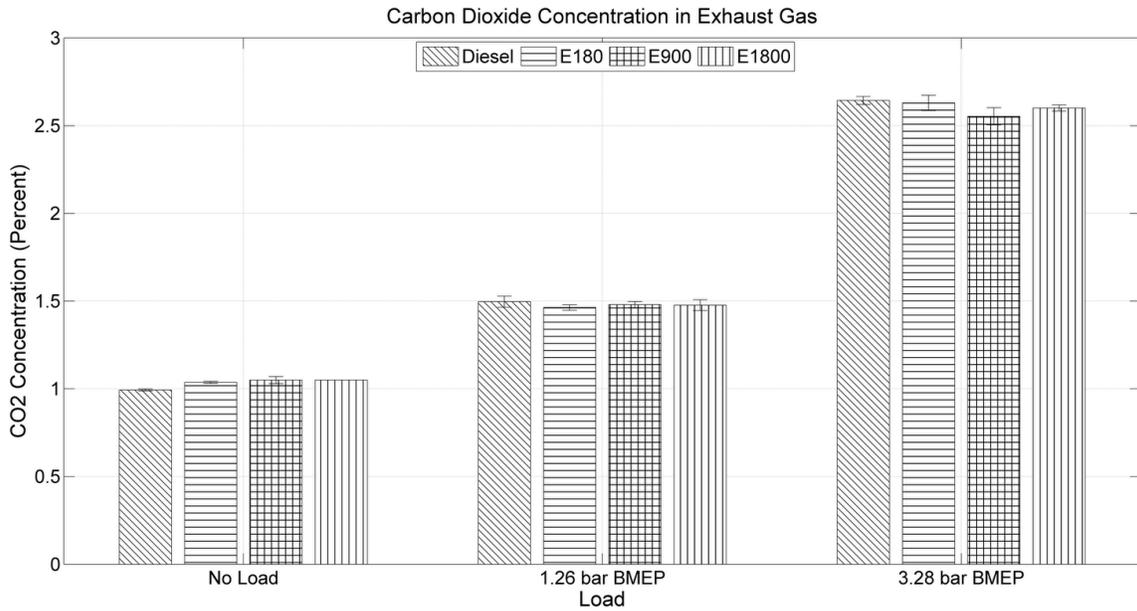


Figure 4.17: Carbon Dioxide Emissions for all fuels across all loads

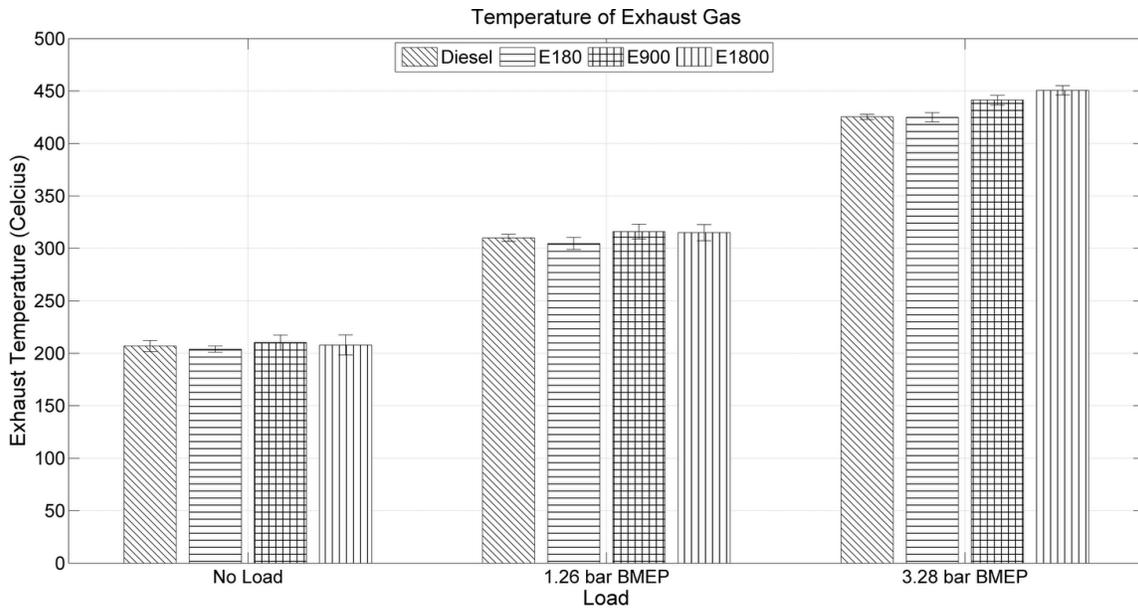


Figure 4.18: Exhaust Gas Temperature for all fuels across all loads

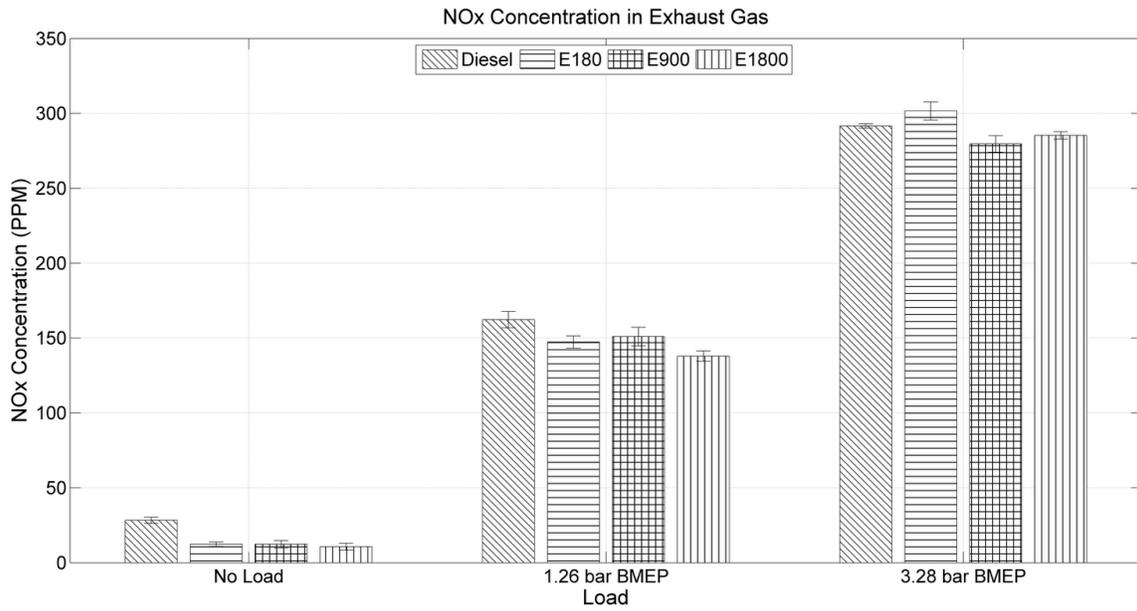


Figure 4.19: NO<sub>x</sub> emissions for all fuels across all loads

## CHAPTER 5

### PERFORMANCE AND EMISSIONS TESTING OF EUGENOL MIXED WITH DIESEL

#### 5.1 Abstract

In this study, eugenol, which is an important component in diesel extracts of wood pyrolysis bio-oil, is mixed with diesel to form three mixtures of varying concentration. These are E5 (5% v/v), E10 (10% v/v) and E20 (20% v/v). The performance and emission characteristics of these mixtures were compared with diesel by testing it in a 10 HP single cylinder diesel engine, operated at 2000 RPM and under four load conditions which corresponded to 0 bar BMEP (no load), 1.26 bar BMEP, 2.52 bar BMEP and 3.78 bar BMEP. The eugenol-diesel mixtures gave out work outputs and mechanical efficiencies similar to that of diesel with a 2-3% variation. E5 and E10 had slightly lower outputs but the performance of E20 and diesel were nearly the same with E20 having a higher mechanical efficiency at 1.26 bar and 2.52 bar BMEP. The Brake Specific Fuel Consumption was slightly lower for E5 and E10 at 1.26 and 3.78 bar BMEP. At 2.52 bar BMEP, the BSFC increased with increasing eugenol concentration. The pressure changes in the cylinder varied with both, the fuel tested as well as the load under which the engine was operated. At 0 bar and 1.26 bar BMEP, E10 and E20 had slightly lower peak pressures while at higher loads of 2.52 bar and 3.78 bar BMEP, the peak pressure for all the fuels were roughly the same. An interesting observation was the significantly longer ignition delays that E10 and E20 went through for all the load conditions. A clear reduction in the hydrocarbon and soot emission was observed with the use of the

eugenol mixtures. Higher the concentration, better were the results and consequently, E20 exhibited the maximum reduction in these emissions when compared to diesel. At loads of 0 bar and 1.26 bar BMEP, there a slight reduction in NO<sub>x</sub> emissions while at 2.52 bar and 3.78 bar BMEP, the NO<sub>x</sub> was slightly higher with reference to the levels emitted by diesel. The use of eugenol-diesel mixtures did not have any effect on the CO and CO<sub>2</sub> levels emitted. The role of eugenol in altering the performance and emissions of an engine was analyzed leading to possible experimentation at different speeds with engines of different capacity and operating conditions that better mimic practical applications.

## **5.2 Literature Review**

It was seen in the previous experiment of this study that diesel extracts of bio-oil have a high concentration of phenolics, one of which was eugenol. It is interesting to find out the specific role that these phenolics play in altering the combustion characteristics. The aim of this experiment is to ascertain the specific role that eugenol plays in this regard. Eugenol is a chemical compound that is largely found in the essential oils of cloves, bay leaf etc. Studies have shown clove bud oil has a very high percentage of eugenol, around 87% [23]. Thus the possibility of using these essential oils and their major chemical extracts as components in fuel blends is explored. Essential oils are the oils extracted from certain plants species by processes involving distillation wherein the volatile aroma compounds are removed from the plant in the form of an oil. These oils have characteristic aromas specific to the source plant. Essential oils are a cost effective option as they are extracted from plants and are used in

numerous industries thereby reducing the effective cost for each application. These plants are usually locally abundant and most of the times have little conflict with the food industry. A few oils have been tested as possible additions to diesel but these are usually triglycerides of plant leaves/seeds which have been studied in [24]. Clove oil was explored in [25]. It was a good choice since it is a non-edible essential oil extracted from a plant that is widely available in parts of Asia and Africa. Clove stem Oil (CSO) was blended with diesel in two ratios, 25% and 50%, by volume and its performance and emissions were tested. At a fixed load, the Brake thermal efficiency was observed to increase with the CSO concentration due to the increased oxygen content in the oil and also the higher energy input (energy value  $\times$  flow rate), as the fuel consumption increased. The same trend was observed for brake specific fuel consumption as well. Compared to diesel, the CSO blends ran cooler with lower exhaust gas temperatures as was expected from their lower energy input values when compared to diesel. Although the HC emissions were lower for CSO blends, a worrying trend was the significant increase in CO and NO<sub>x</sub> concentrations. The higher combustion temperatures and higher oxygen content explained the increased NO<sub>x</sub> while the high CO content was attributed to the increased ignition delay resulting in making the mixture too lean beyond the lean limit. An analysis of the CSO revealed that the primary component of the oil was eugenol (80% approximately). This would translate into a eugenol concentration of 20% and 40% respectively. A couple of more preliminary studies performed by the same author before this ([26] and [27]) have shown similar results and have also highlighted the possibility that clove stem oil cannot be used directly in very high concentrations in diesel

engines due to its low cetane number and high density relative to diesel and also that it might not be as cost effective as pure diesel despite monetizing its environmental advantages. It was deemed worthwhile to study the independent effect that eugenol had on the performance of a compression ignition engine as opposed to its form as an essential oil. Also in this study, eugenol was one of the major phenolic compounds found in the diesel extracts of bio-oil with diesel mixture that was tested. By studying eugenol in isolation will shed light on the direct impact it has on diesel engine combustion characteristics, especially in a smaller capacity engine as is used in this study.

[28] and [29] have explored this idea of using eugenol as an additive and not as a fuel blend component. The percentage of eugenol used in diesel was 0.2%. It was observed that the heat release rate was faster and the ignition delay shorter than diesel. The bulky structure of eugenol was said to decrease the Van-der-Waal's forces in the diesel fuel thereby resulting in better breaking up of the fuel and better mixing of the fuel resulting in faster combustion. Also the higher oxygen content in eugenol was believed to have caused the relatively high total or cumulative heat release that was observed. At higher speeds of 3000 rpm, the eugenol blend exhibited a lower BSFC than diesel whereas at lower speeds the BSFC was comparable to diesel. However the eugenol blend ran hotter than diesel with higher total heat release and resulted in higher NO<sub>x</sub> emissions and lower HC, CO and smoke emissions. The data for these are not presented but it is prudent to know the exact emissions released by eugenol. This can also be compared to other bio-oils tested in this study. Also previously, when eugenol was used directly, it was done so at very low concentrations. In the present study, three ratios of

eugenol and diesel are studied, namely, E5, E10 and E20. This will allow the analysis of the effect of direct eugenol at higher concentrations where it is treated as a fuel blend with diesel and not an additive. Since the role of eugenol as a stand-alone chemical additive is of prime interest, the chemical is used directly and not in its essential oil form (like clove oil) , which was the case in previous studies. For the first time, pure eugenol is being used in these concentrations, with the aim of a complete performance and emissions test.

### **5.3 Experimental Procedure**

For this experiment, the same experimental setup was used, as described in Chapter 2. Commercial grade Eugenol was purchased, the properties of which are highlighted in Chapter 3. Since the aim of this experiment is to test eugenol as a fuel blend and not as an additive, it was mixed in higher concentrations with diesel. Three concentrations were chosen for this initial study, namely, 5%, 10% and 20% by volume with diesel. These three mixtures have been named E5, E10 and E20 for quick reference. A speed of 2000 RPM was chosen to be a reasonable and moderate engine test speed. However, more evenly spaced out load conditions were tested. Since the use of eugenol in higher concentrations with diesel and subsequently conducting a comprehensive performance and emissions test on the resulting mixture is a fairly new attempt, the tests were conducted at more load conditions than before. The water dyno was operated such that the load on the engine corresponded to 0 bar, 1.26 bar, 2.52 bar and 3.78 bar Brake Mean Effective Pressure.

The engine was warmed up and set at the particular test conditions using diesel. The diesel was then removed and replaced by the Eugenol diesel mixture. The engine was allowed to run for an additional 10 minutes to burn the residual diesel in the fuel supply system and for the engine to settle down on the new fuel, before data was collected. As before, in-cylinder pressure data was averaged and smoothed over 25 random combustion cycles. Three trials were taken and averaged for all other readings.

## **5. 4 Results and Discussion**

### **5.4.1 Performance**

The first performance characteristic studied is the indicated work done by the engine during the combustion (Figure 5.1). As more heat is released at higher loads, the work done by the combustion of a fuel at a higher load is clearly higher. More importantly, it can be seen that at no load, diesel has the highest work output, with a marginal drop exhibited by the eugenol mixtures. E20 has the lowest output at 32.5 Joules. At 1.26 bar and 2.52 bar BMEP, E20 still exhibits the lowest work output but E5 and E10 have a higher output than the other fuels in the two cases respectively. A trend almost identical to 1.26 bar BMEP is observed at 3.78 bar BMEP. Overall, it must be noted that the differences in indicated work are minor and are within 2-3% at higher load conditions. These minor variations could be caused by the increased density of the eugenol mixture, leading to variabilities in atomization of the fuel. As before, the brake work is kept constant using the water dynamometer. The mechanical efficiency then becomes a function of the indicated work alone, which is shown in Figure

5.2. At 1.26 bar and 2.52 bar BMEP, the mechanical efficiencies are roughly the same, varying a couple of percentages from each other but E5 and E10 consistently produced slightly lower efficiencies than diesel, for all loads. At 3.78 bar BMEP, this difference was slightly more pronounced. The maximum efficiency of 98.3% was observed by E20 at 3.78 bar BMEP.

The brake specific fuel consumption, sheds light on the interplay between the brake work and the fuel consumed by the engine to produce that work and is shown in Figure 5.3. The BSFC behavior is dependent on the load under which the engine operates. Similarities are seen at 1.26 bar and 3.78 bar BMEP, where diesel and E20 have similar BSFC values while E5 and E10 produce slightly lower BSFC values which are again similar to each other. In the case of 1.26 bar BMEP, E10 has the lowest BSFC of 0.487 kg/kW.hr and E5 has a value of 0.491 kg/kw.hr. At 3.78 bar BMEP, the lowest BSFC is seen for E5, 0.221 kg/kW.hr while E10 exhibits a BSFC of 0.251 kg/kW.hr. At 2.52 bar BMEP, the fuel consumption increases slightly with increasing eugenol concentration. The value varies from 0.30 kg/kW.hr to 0.36 kg/kW.hr. This pattern seems to indicate that lower concentrations of eugenol are more effective in reducing the fuel consumption for 1.26 bar and 3.78 bar BMEP but the effect is not that apparent at 2.52 bar BMEP. Overall, the eugenol mixtures have a higher fuel consumption which could be attributed to their energy density/caloric value.

### 5.4.2 In-Cylinder phenomena

As mentioned in Chapter 2, a pressure sensor is used to collect data on the in-cylinder pressure variation during the combustion cycle. As expected, at higher loads, a given fuel produces higher peak pressures as more energy is released to produce more work. In Figures 5.4a-b, 5.5a-b, 5.6a-b and 5.7a-b the variation of the in-cylinder pressure for the different cases are shown on the basis of both load and fuel. The behavior of the mixtures with higher eugenol concentration, namely, E10 and E20, are different from the baseline diesel and E5 and this behavior is also highly load dependent. At no load conditions, the peak pressure decreases slightly with increasing eugenol concentration and also a slightly longer ignition delay is observed in the case of E10 and E20. The ignition delay for the fuels is shown in Figure 5.8. However this longer ignition delay does not seem to translate into a higher peak pressure. At 1.26 bar BMEP, the peak pressures are nearly identical but E20 again displays an even longer ignition delay and a smaller peak pressure. The pressure is about 5.605 MPa while diesel's peak pressure was slightly higher at 5.708 MPa. In these two cases, it is also seen that the rate of pressure rise of E20 is also slightly lower than the other fuels under consideration. This anomalous behavior of a longer ignition delay with a lower peak pressure and slower pressure rise indicates poor atomization where the relatively larger droplets take longer to ignite and at the same time do not combust cleanly due to poor mixing of these large droplets producing lower energy output. Also the peak pressure could be attained past TDC when the instantaneous volume is higher, resulting in lower pressure. At 2.52 bar BMEP, all the fuels produce roughly the same peak pressure but longer ignition

delays are observed for E10 and E20. Similarly, at 3.78 bar BMEP, despite the longer ignition delay for E10 and E20, the peak pressures are the same and E20 actually has the highest peak pressure of 6.61 MPa. As the eugenol concentration increases, the peak pressure produced also increases. Thereby, diesel has the lowest peak pressure of 6.45 MPa, in this case. This is in complete contrast to the behavior observed at no load. A possible explanation for this is that, as before, the added density of eugenol results in larger droplets which explain the longer ignition delay but at higher load the engine draws in more air due to the wider open throttle position to maintain the same speed. This increased flow of air results in better mixing of the larger droplets and could possibly also break the fuel down to a more uniform fuel-air charge environment which results in comparable or even higher peak pressures. If this is the case, it is possible that the ignition delay is affected not only by physical factors like density and viscosity but also by other thermo-chemical properties which influence the energy needed to ignite the fuel droplets.

The heat release rate is plotted against the crank angle in Figure 5.9a-b, 5.10a-b, 5.11a-b and 5.12a-b for different cases on the basis of load and fuel. Firstly, the warmer engine conditions at higher loads results in a shorter ignition delay for all the fuels tested. This shifts the point of highest heat release farther from the Top Dead Centre. Analyzing the plots for the fuels for a given load, E20 displays slightly different behavior than the other fuels. At no load, E20 has a significantly longer ignition delay but has a lower peak heat release rate. This is in agreement with the low peak pressure observed in Figure 5.6a and follows the same

reasoning. At 1.26 bar and 2.52 bar BMEP, diesel and E5 have nearly identical curves. E10 and E20 display progressively longer delays. Finally, at 3.78 bar BMEP, the ignition delay is more uniform for the four fuels and the peak heat release rate is directly proportional to the eugenol concentration. The explanation of higher air flow into the chamber at higher loads which was hypothesized for the pressure curve behavior can adequately explain these observations too, made at 3.78 bar BMEP. As mentioned for the pressure curves at 3.78 bar BMEP, the heat release rate can also be influenced by chemical kinetics. This could explain the higher peak heat release rate observed for a given fuel at 3.78 bar BMEP. The ignition delay for the fuels across all the load conditions is also shown in Figure 5.8. The shortening of the ignition delay with increasing load is apparent. At no load and 1.26 bar BMEP, diesel and E5 have similar ignition delays of about 10.8 -11 degrees but at higher loads, E5 has a longer delay when compared to diesel. E20 again exhibits discordant behavior wherein at no load, the delay is 12 degrees and this increases at 1.26 bar BMEP, to 12.4 degrees. Further at 2.52 bar and 3.78 bar BMEP. The delay again decreases to 11.4 and 11 degrees respectively. The effect of this is seen in the pressure and heat release rate curves of E20.

The cumulative heat release curves which are also plotted against crank angle, are shown in Figures 5.13a-b, 5.14a-b, 5.15a-b and 5.16a-b. For all load conditions except 3.78 bar BMEP, the eugenol mixtures have a lower cumulative heat release rate and at best, are comparable to diesel. This is mainly due to a combination of atomization and ignition delay. However, information on the calorific value of the mixtures can provide a better picture of the energy

that can be potentially released and whether the calorific value of the mixtures is significantly lesser than diesel. As before the behavior at 3.78 bar BMEP is in line with the observation and reasoning for pressure and heat release rate and increases with increasing eugenol concentration.

### **5.4.3 Emissions**

The main emission species which are measured and analyzed in this experiment are Hydrocarbons, Carbon monoxide, Carbon dioxide,  $\text{NO}_x$ . The actual temperature and opacity of the exhaust gas is also measured and recorded. Figure 5.17 shows the HC concentration emitted by the fuels across loads. The overall trend observed is that the eugenol mixtures produce much lower HC emissions and the eugenol concentration and the HC emitted are inversely proportional to each other. This means the eugenol mixtures burn cleaner than diesel. A possible explanation could be the oxygen-rich nature of eugenol which results in more complete combustion of the hydrocarbons. A significant drop is observed for 1.26 bar BMEP where diesel produced 24 PPM of HC whereas E20 produced just 8 PPM. The drop is much lower at 3.78 bar BMEP where diesel produced about 8.5 PPM while E20's emissions was marginally lower at 7 PPM.

The Carbon monoxide emissions decreased significantly with increasing load as can be seen in Figure 5.18. This is explained by the warmer engine temperatures and higher air flow at these higher load conditions. However, the mixing of eugenol with diesel had almost no

effect on the CO levels which remain fairly constant at a given load. The Carbon dioxide emissions can be seen in Figure 5.19. As load increases, the CO is oxidized resulting in less CO emissions and more CO<sub>2</sub> emissions. The variations between fuels for a given load is minor but are not perfectly zero. At lower loads, the fuels tend to have slightly lower CO<sub>2</sub> concentrations than that of diesel and at higher loads, the concentration is slightly higher. This can possibly be explained by the increased oxygen in higher eugenol concentration blends which oxidizes the carbon more effectively to form carbon dioxide. Hence, the addition of eugenol has a slight effect on the CO and CO<sub>2</sub> emissions.

The exhaust temperature shown in Figure 5.21, does not exhibit a clear pattern across the various fuels and load conditions. At no load conditions, the eugenol mixtures run slightly cooler than diesel. Diesel combusted with a temperature of 107.5° C while the lowest temperature of 97° C was seen in the case of E5. At 1.26 bar BMEP, the eugenol mixtures run hotter than diesel and it appears that the temperature increases with the eugenol concentration except for E10 where the temperature was about 7.8° cooler than diesel's 155.3° C. At a load of 3.78 bar BMEP, the eugenol mixtures again showed slightly lower temperatures than diesel. This trend of the exhaust gas temperature observed can be explained by observing the diffusion combustion portion of the heat release rate curves. The magnitude of the heat release rate once it rises up to a small peak in the later, diffusion stage, fairly matches the trend for exhaust temperature. Lesser the rate during the diffusion combustion stage, less heat escapes via the exhaust gas stream.

$\text{NO}_x$  emissions are largely dependent on the combustion temperature in the cylinder. The peak heat release rate is a clear indicator of this aspect. From Figure 5.22, we see that E20 has the lowest peak heat release rate and correspondingly, it exhibits zero  $\text{NO}_x$  at no load. At 2.52 bar BMEP, the progressive increase in  $\text{NO}_x$  from diesel to E20 is similar to the increase seen in the peak heat release rate at the same BMEP. The sharp spike seen at 3.78 bar BMEP where E20 produces about 400 PPM of  $\text{NO}_x$  is explained by the similar spike seen in E20's peak heat release rate. The behavior of E180 at no load cannot be very clearly explained by the heat release rate data. As mentioned before, other factors like the energy needed to break up the nitrogen bonded to the fuel and the process of oxidation of the nitrogen in the air can also influence the  $\text{NO}_x$  emitted. This trend of increasing  $\text{NO}_x$  does not bode well for the use of these eugenol mixtures especially at high loads.

The opacity of the exhaust gas from the engine was measured by a smoke opacity meter, as explained in Chapter 2. These observations are presented in Figure 5.23. This opacity is directly related to the soot concentration in the smoke. At no load and 1.26 bar BMEP, the opacity is practically zero. This follows from the relatively low amount of fuel that is burnt at low loads, that too under relatively leaner conditions. At 2.52 bar BMEP, the maximum opacity is seen in the case of diesel and for the eugenol mixtures the opacity progressively decreases with increasing concentration. Diesel has an opacity of 4.22% while E5, E10 and E20 have opacities of 2.21%, 1.75% and 1.47% respectively. At 3.78 bar BMEP, the opacity further increases as more fuel is burnt under fuel-rich conditions. Again, diesel emits the

most soot with a smoke opacity of 10.71%. E5 and E20 have similar opacities of 6.21% and 6.46% respectively but E10 shows an abnormal spike with a value of 8.93%. The general decrease in the opacity of the eugenol mixtures can be explained by their high oxygen content which does not allow the formation of solid soot particles which are characteristic of highly incomplete combustion.

## **5.5 Conclusion**

The combustion characteristics of eugenol mixed in diesel was studied by conducting an experiment which focused on the major performance and emissions attributes. Three mixtures of varying concentration were tested. The major inferences and conclusions drawn from this study, are presented below.

1. At lower loads (0 bar and 1.26 bar BMEP), the eugenol mixtures produce slightly lower indicated work while at higher loads, they produce slightly higher work outputs. Overall the work output is comparable to diesel and lies within 2-3%. Consequently, the mechanical efficiencies of the four fuels tested, are also comparable. It is seen that the BSFC for E5 and E10 were lower than that of diesel at 1.26 bar and 3.78 bar BMEP while E20 showed behaviour similar to diesel. At 2.52 bar BMEP, the eugenol mixtures showed progressively larger BSFC as the concentration increased. This seems to indicate that lower eugenol concentrations tend to have better fuel consumption when compared to diesel.

2. The in-cylinder pressure variation of the eugenol mixtures was heavily dependent on the load applied on the engine. At no load and 1.26 bar BMEP, E10 and E20 showed slightly lower peak pressures while at 2.52 bar and 3.78 bar BMEP, the peak pressures were roughly the same with E10 and E20 tending to be on the higher side. Also across all loads, E10 and E20 exhibited significantly longer ignition delays. These fuels in particular also exhibited higher peak heat release rates at higher loads than the others.
3. Two main inferences can be drawn from the emissions analysis. First, for all load conditions, there was a significant decrease in the HC and soot produced by the engine when the eugenol mixtures were used. Higher the concentration, better were the HC and soot emissions. Secondly, at low loads (0 bar and 1.26 bar BMEP), there was a slight decrease in the NO<sub>x</sub> emissions when compared to diesel but at higher loads the NO<sub>x</sub> emitted was slightly higher than diesel. CO<sub>2</sub> levels were slightly elevated at higher loads and CO levels remained fairly constant.
4. Since the performance of the eugenol mixtures is comparable to diesel, there is no distinct pay-off or sacrifice in this regard except for the higher fuel consumed, especially at higher loads. The reduction in HC and soot is encouraging. However, the emissions at higher loads seem to be worse than diesel for all concentrations. This coupled with the higher fuel consumed, calls for further experimentation at different speeds and at more load points to better understand the behaviour of eugenol. Also

other major components of bio-oils like guaiacol and 4-vinylguaiacol can be tested separately to understand their contribution to performance and emission changes.

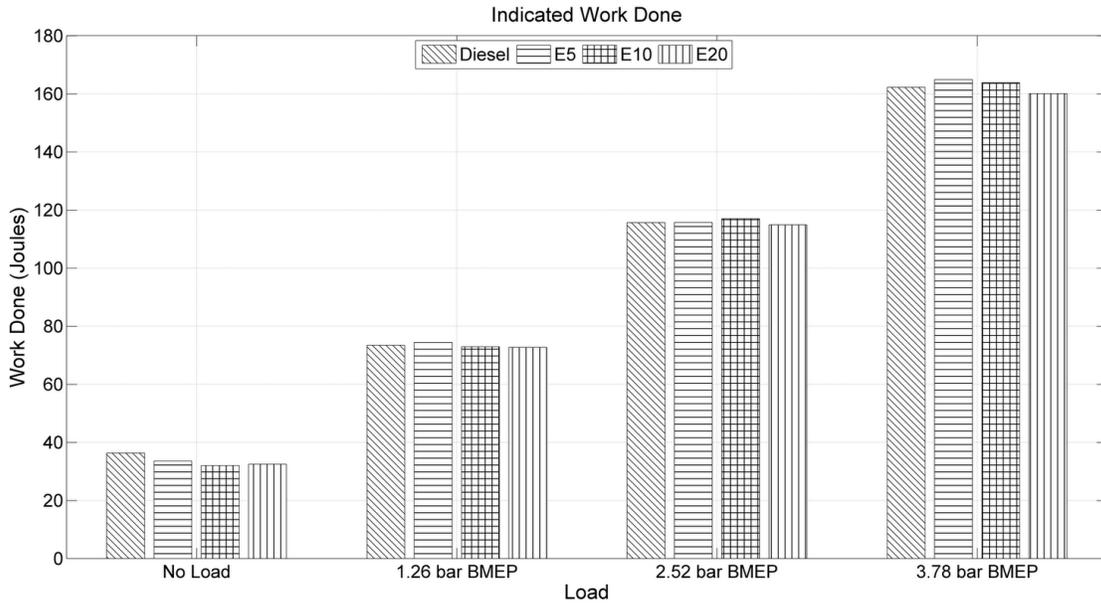


Figure 5.1: Indicated Work for all fuels at different BMEPs

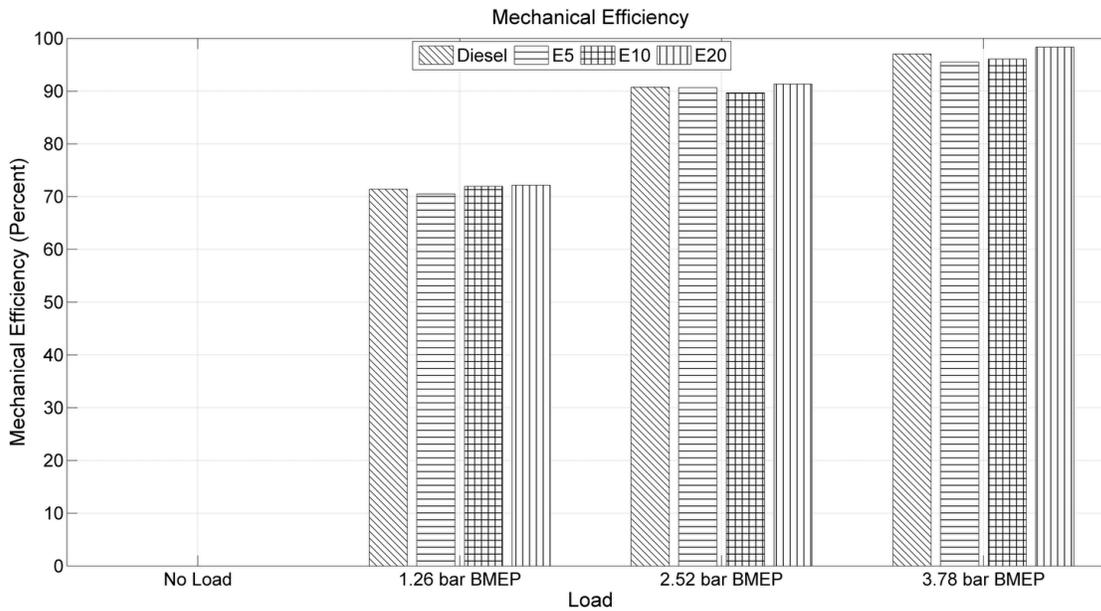


Figure 5.2: Mechanical Efficiency for all fuels at different BMEPs

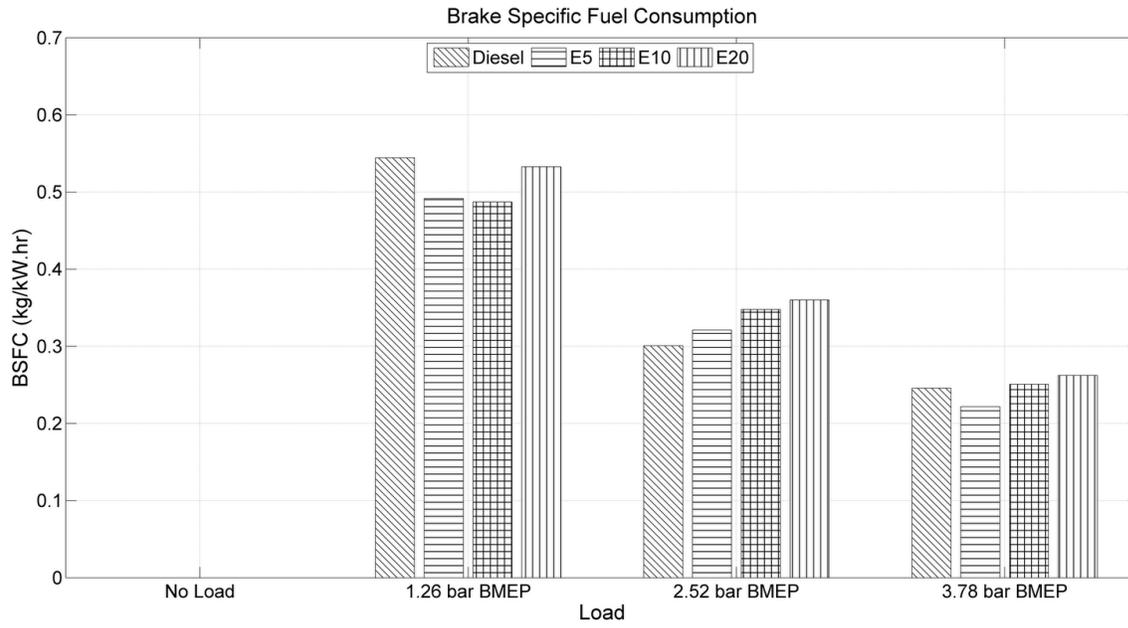


Figure 5.3: Brake Specific Fuel Consumption for all fuels at different BMEPs

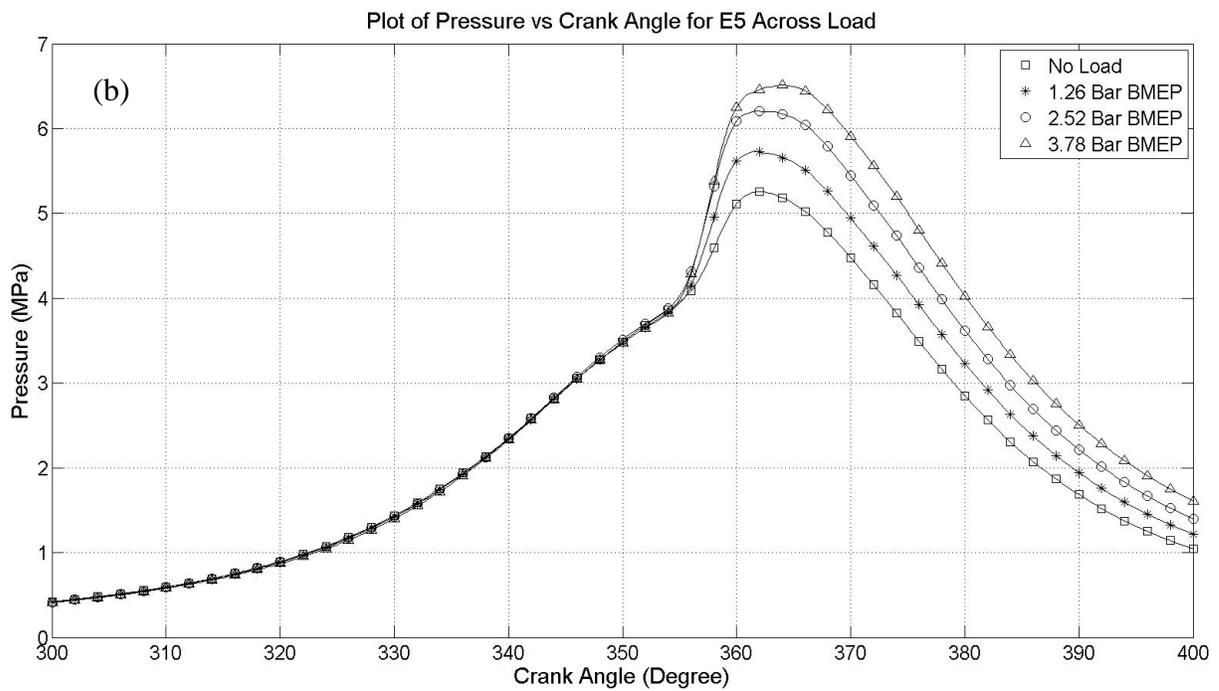
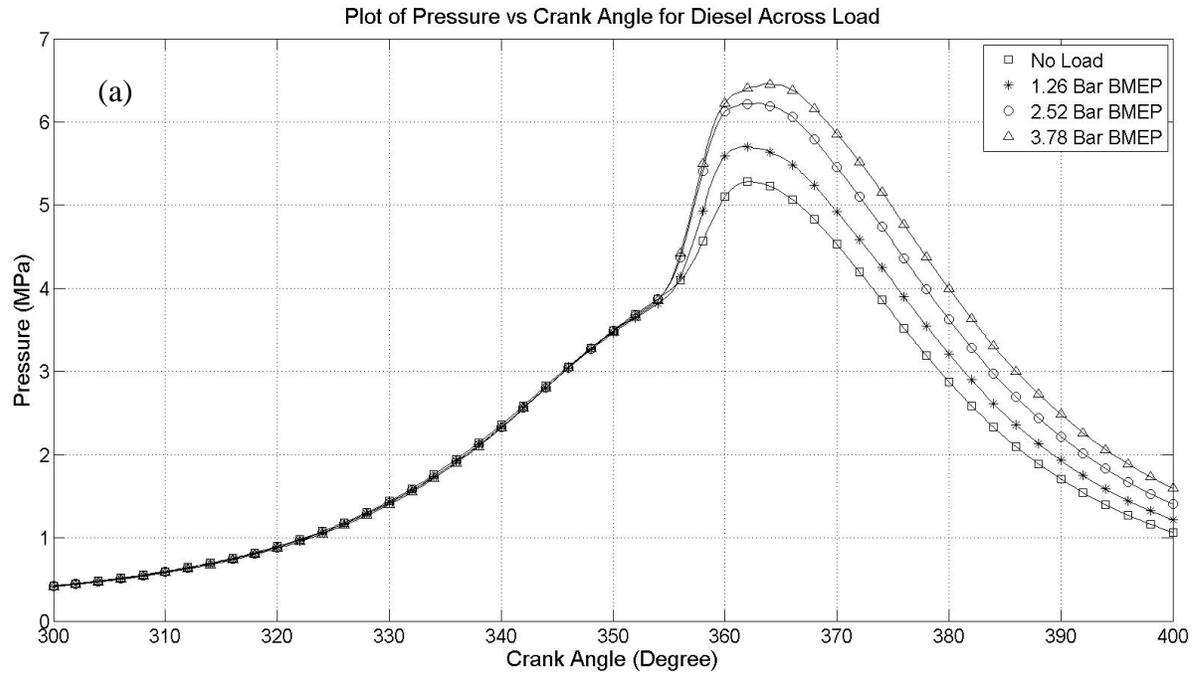


Figure 5.4: In-Cylinder pressure for (a) Diesel (b) E5 at different BMEPs

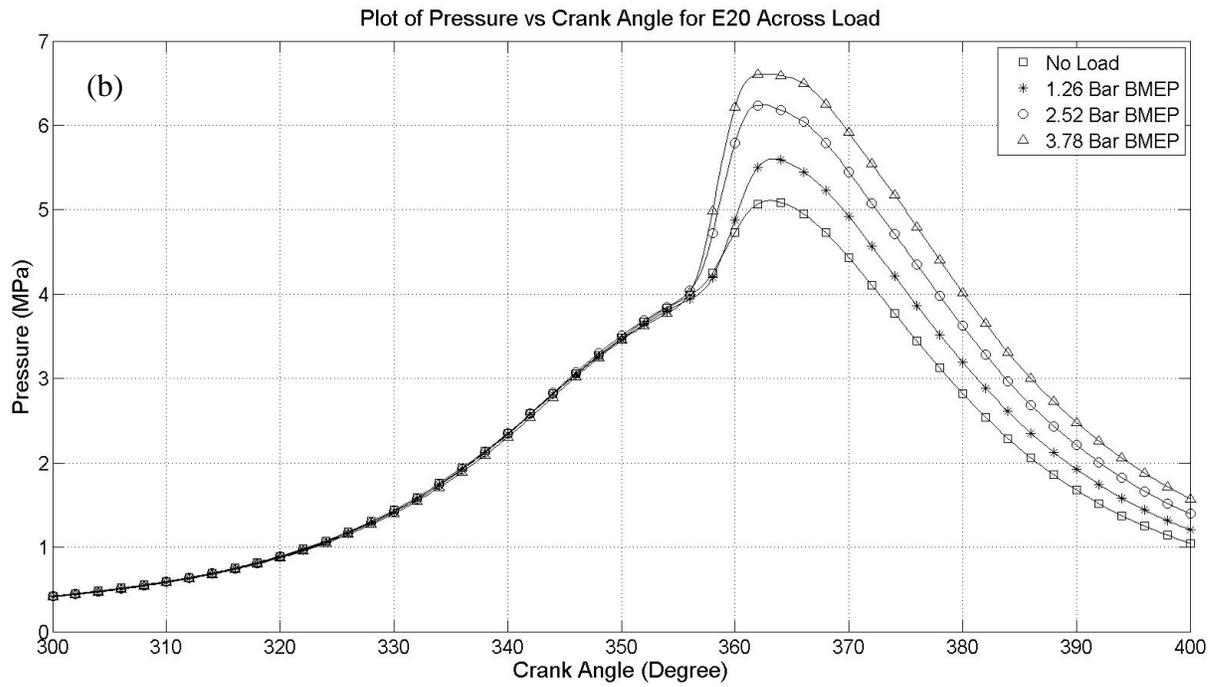
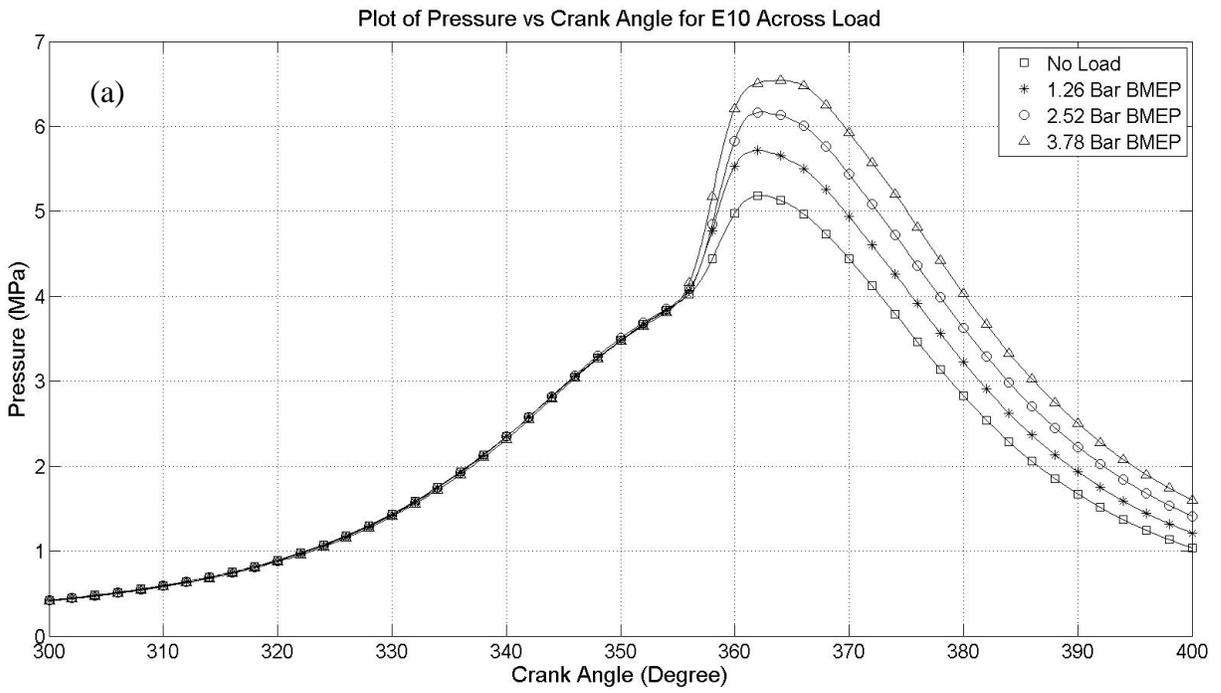


Figure 5.5: In-Cylinder pressure for (a) E10 (b) E20 at different BMEPs

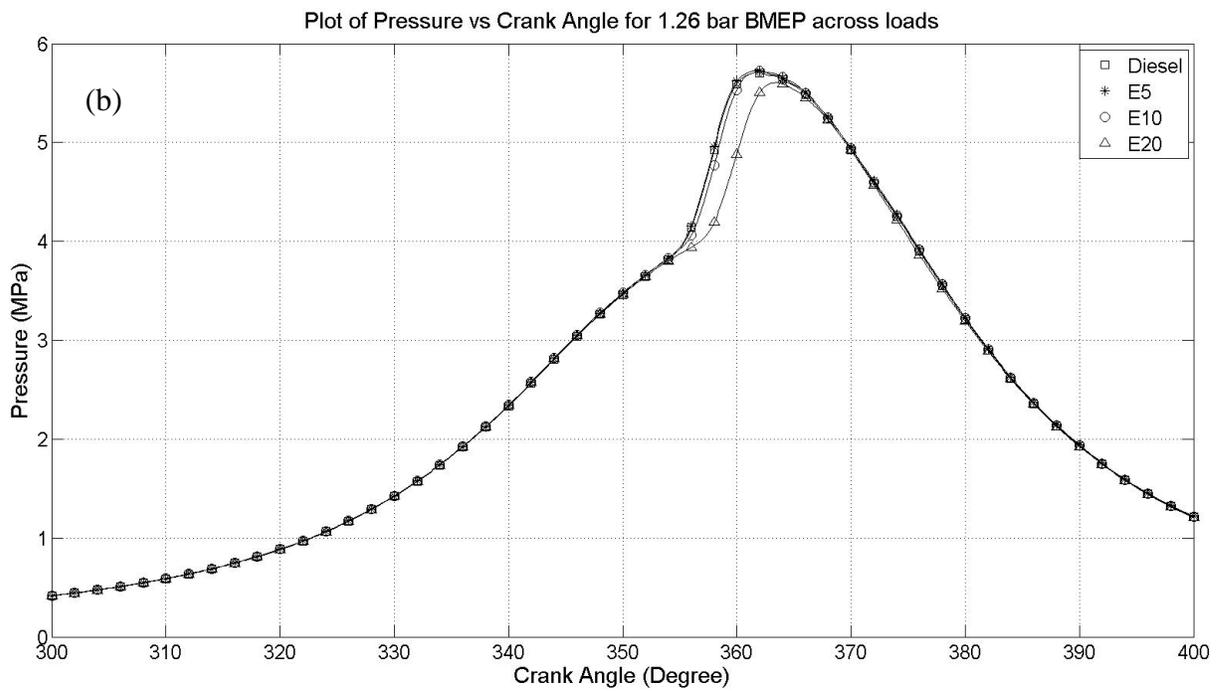
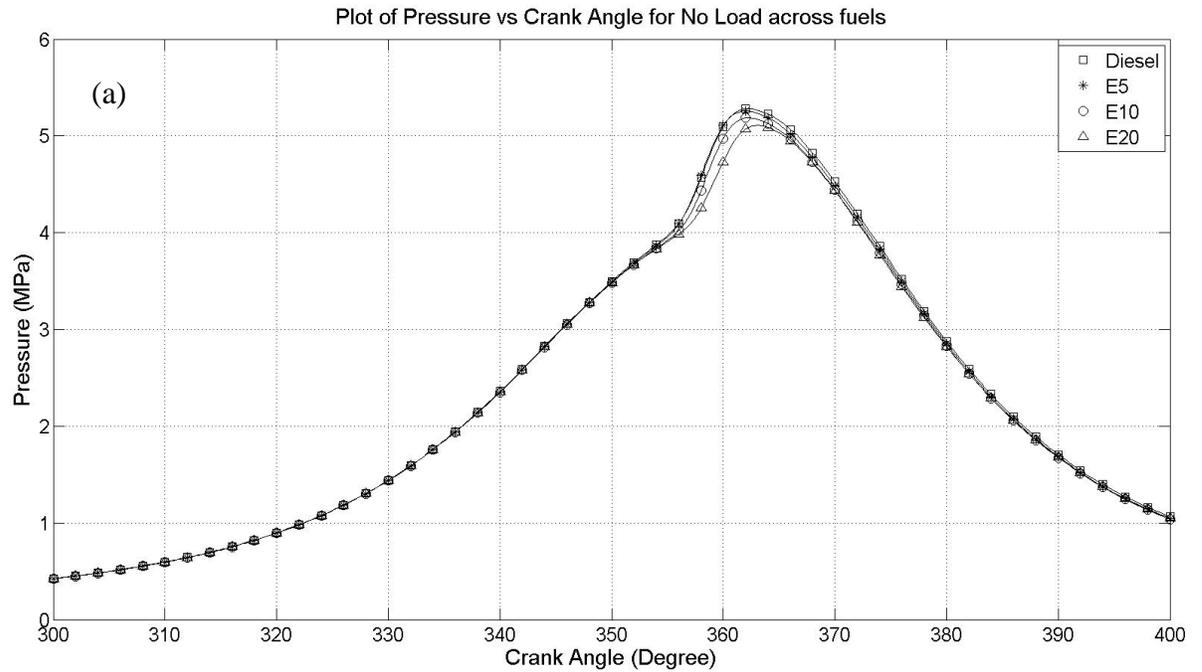


Figure 5.6: In-Cylinder pressure at (a) 0 bar (b) 1.26 bar BMEP for all the fuels

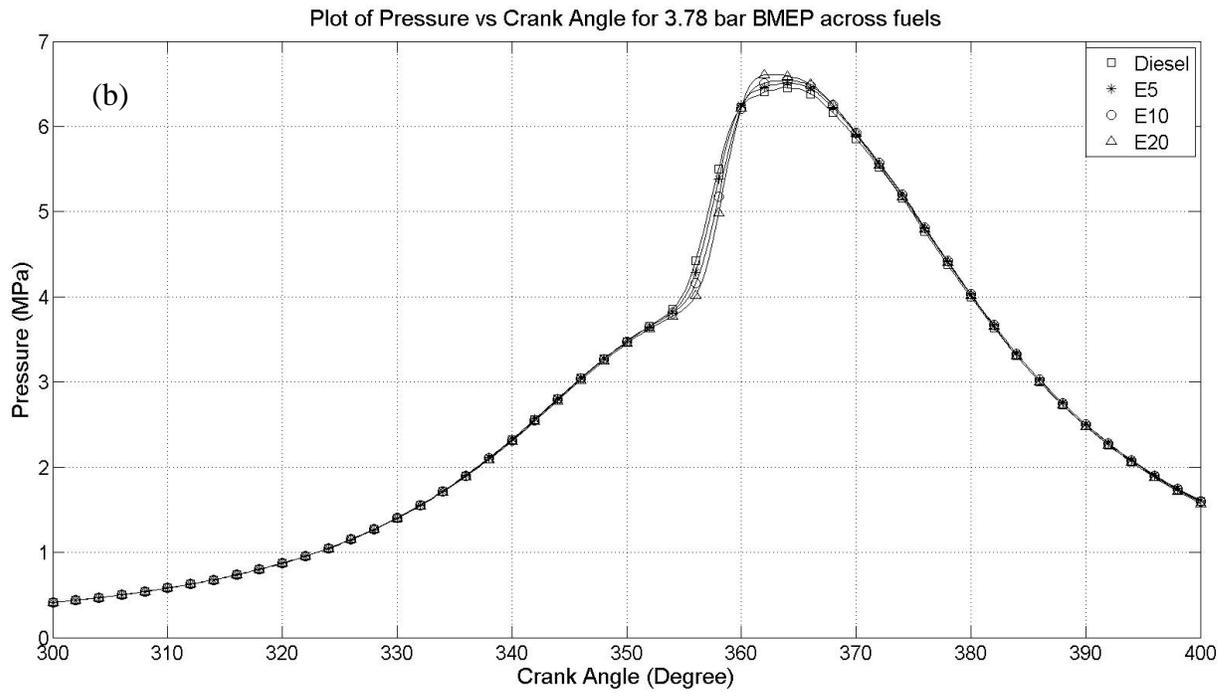
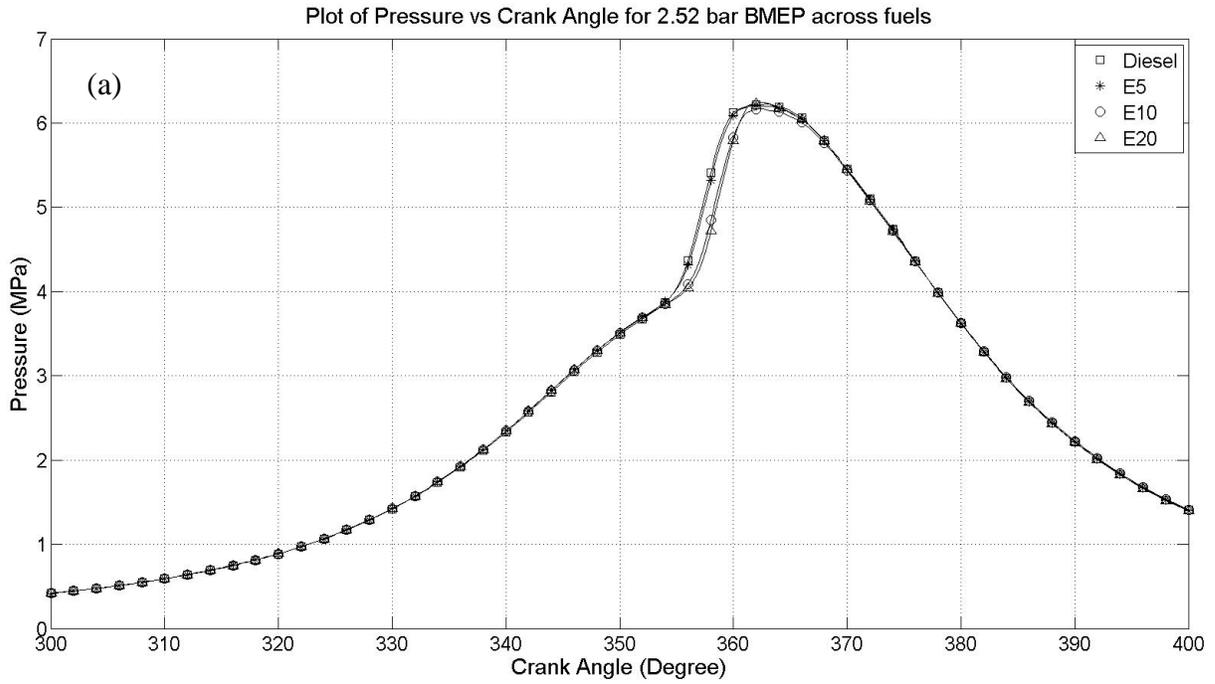


Figure 5.7: In-Cylinder pressure at (a) 2.52 bar (b) 3.78 bar BMEP for all the fuels

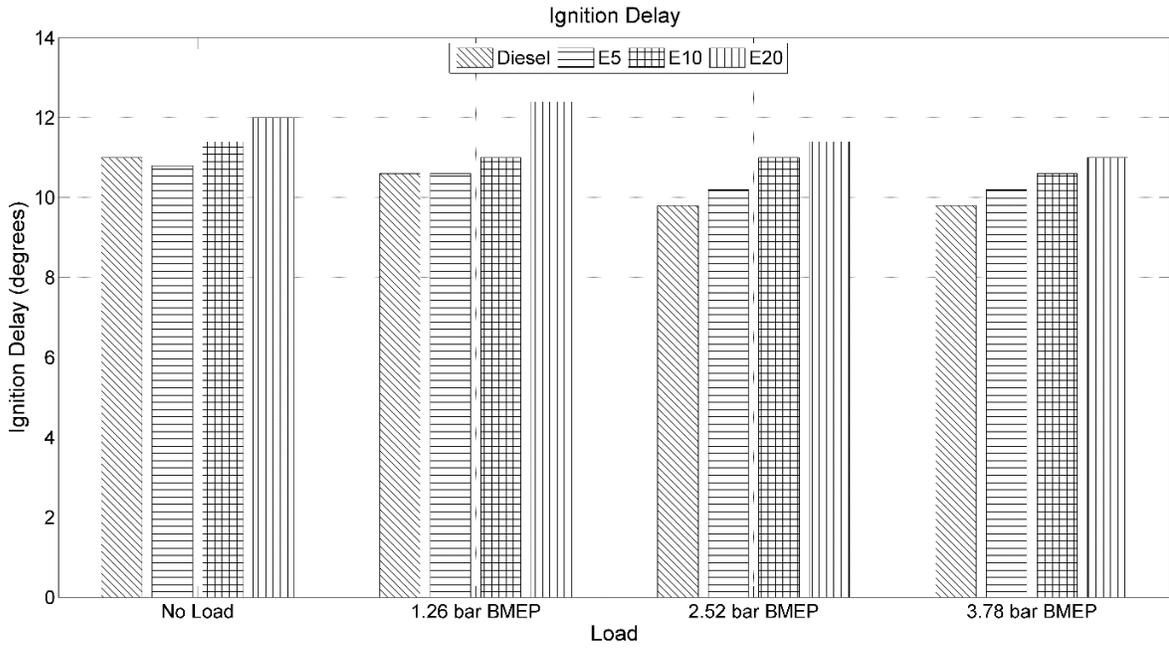


Figure 5.8 : Ignition Delay for all fuels at different BMEPs

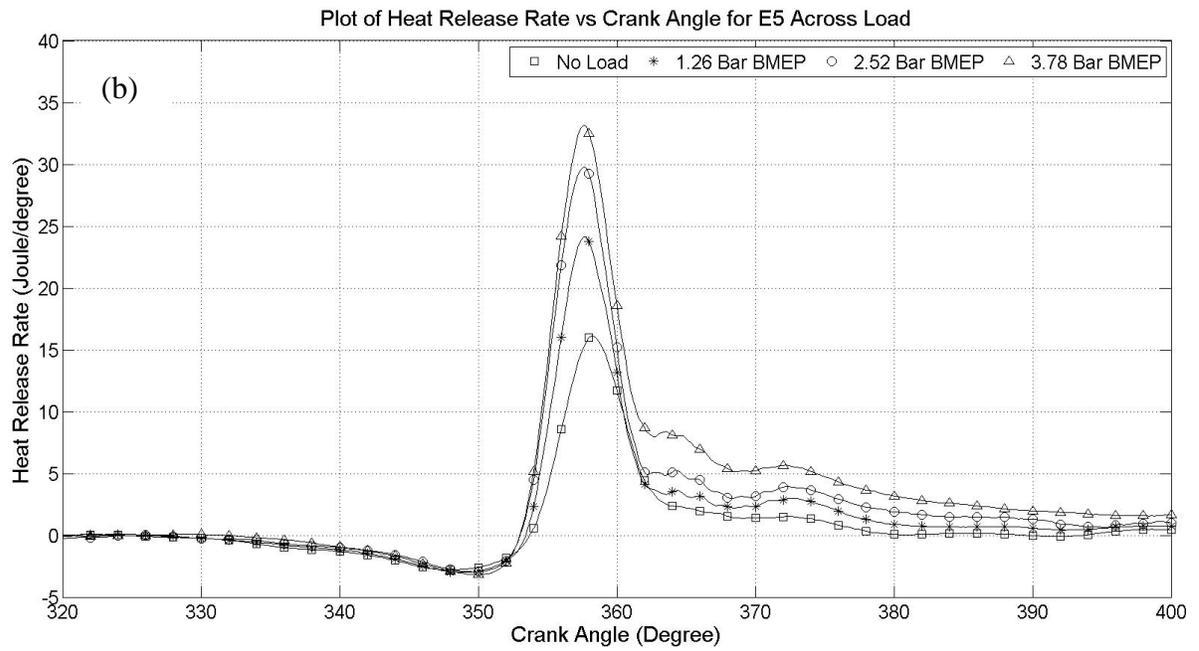
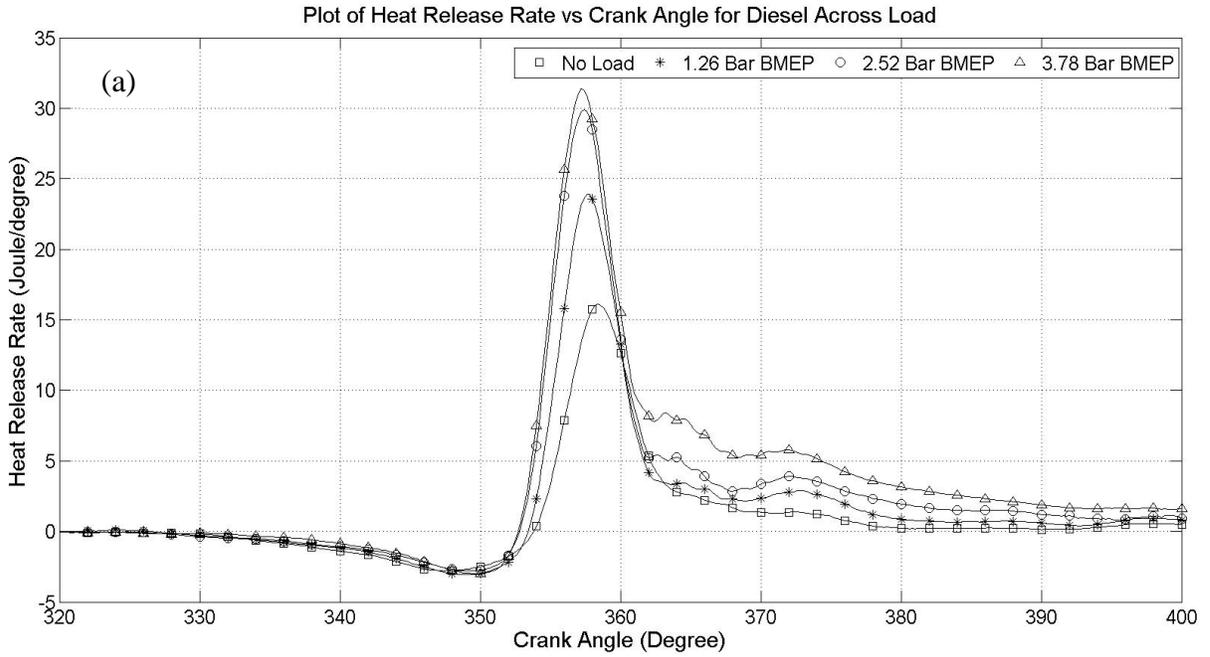


Figure 5.9: Heat release rate for (a) Diesel (b) E5 at different BMEPs.

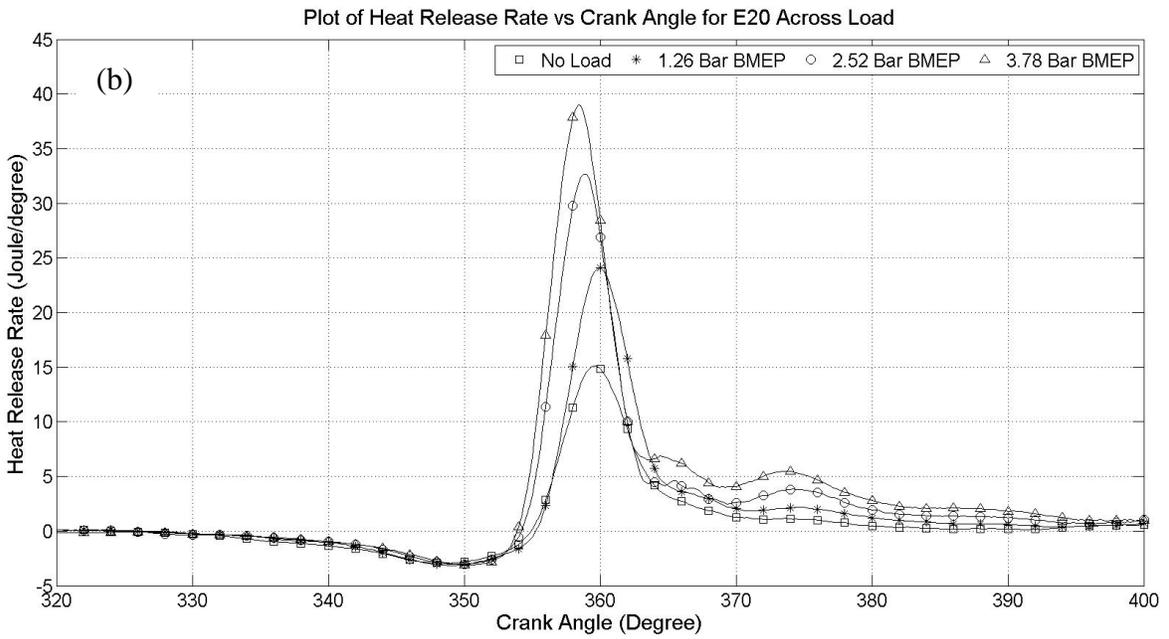
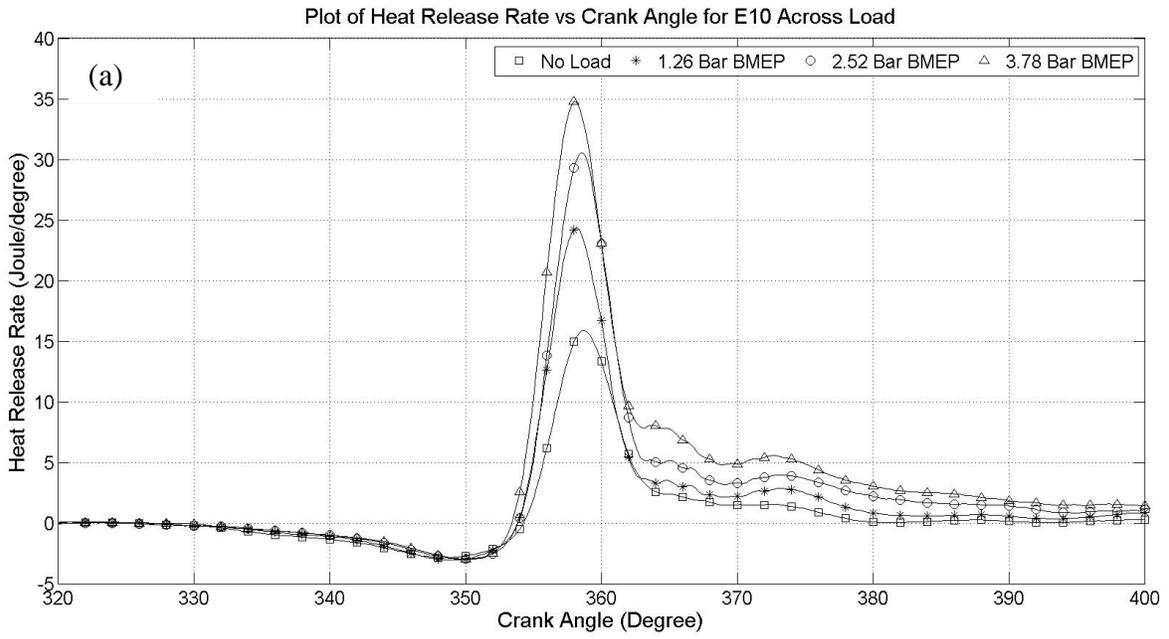


Figure 5.10: Heat release rate for (a) E10 (b) E20 at different BMEPs

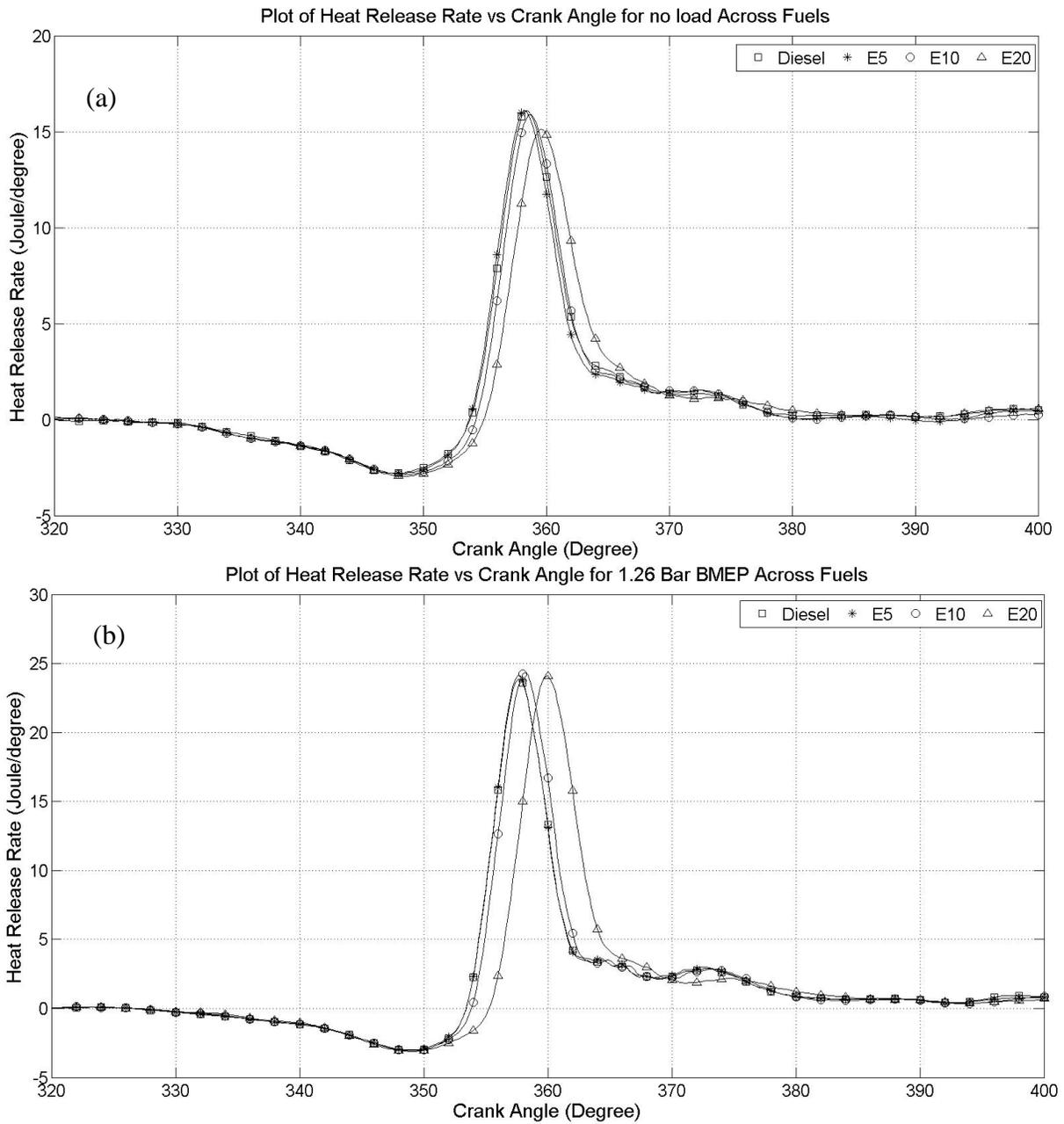


Figure 5.11: Heat release rate at (a) 0 bar (b) 1.26 bar BMEP for all fuels

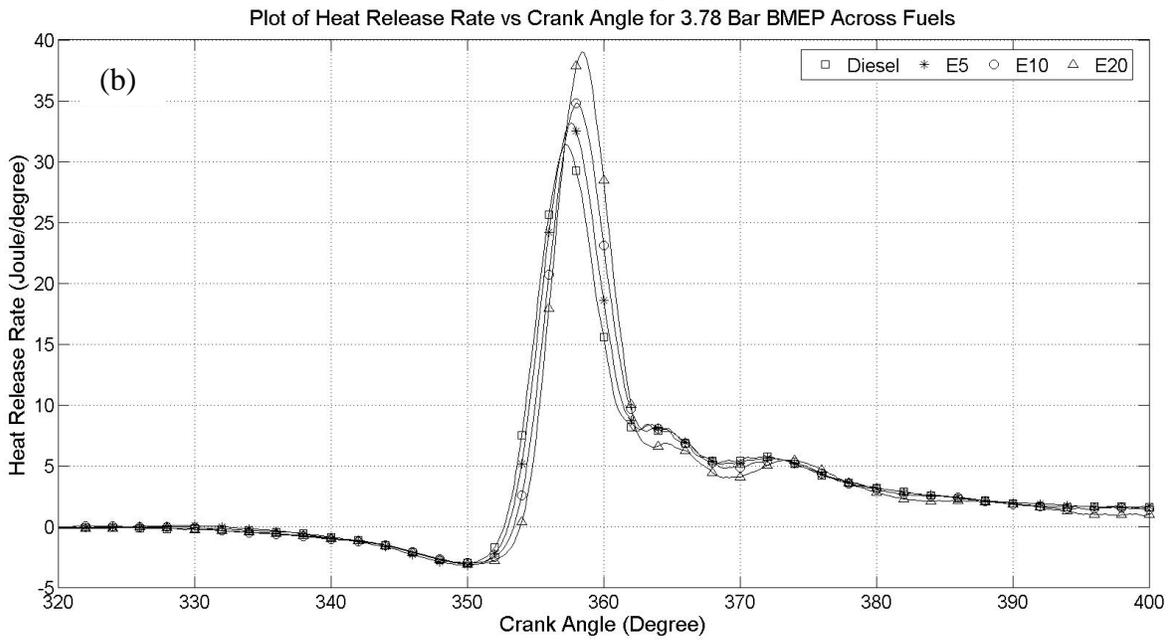
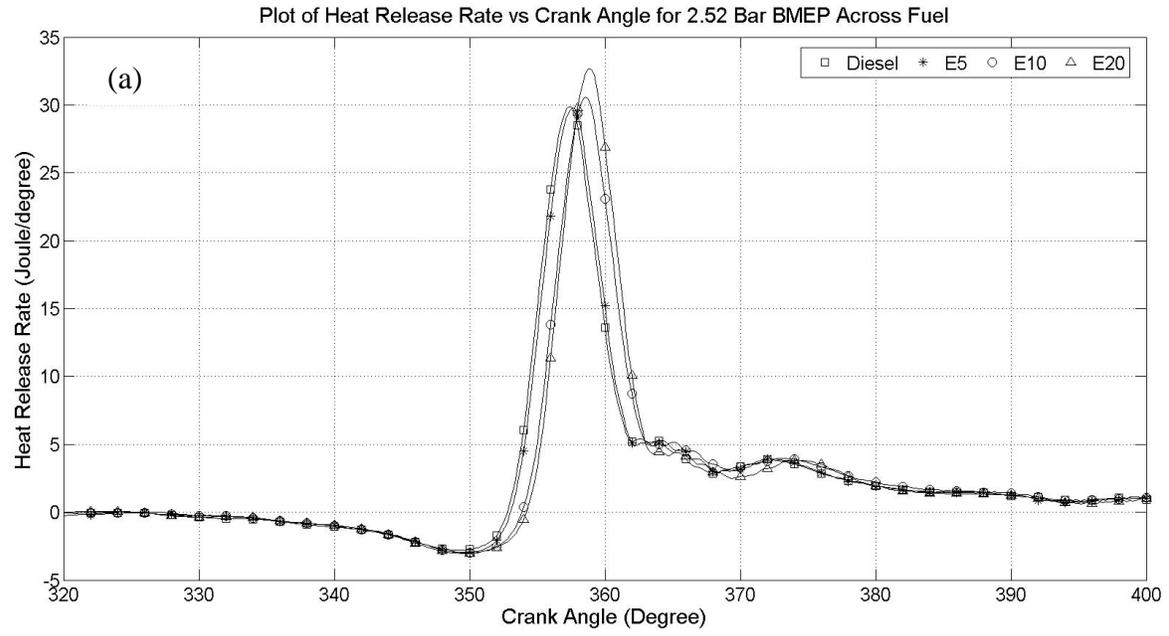


Figure 5.12: Heat release rate at (a) 2.52 bar (b) 3.78 bar BMEP for all fuels

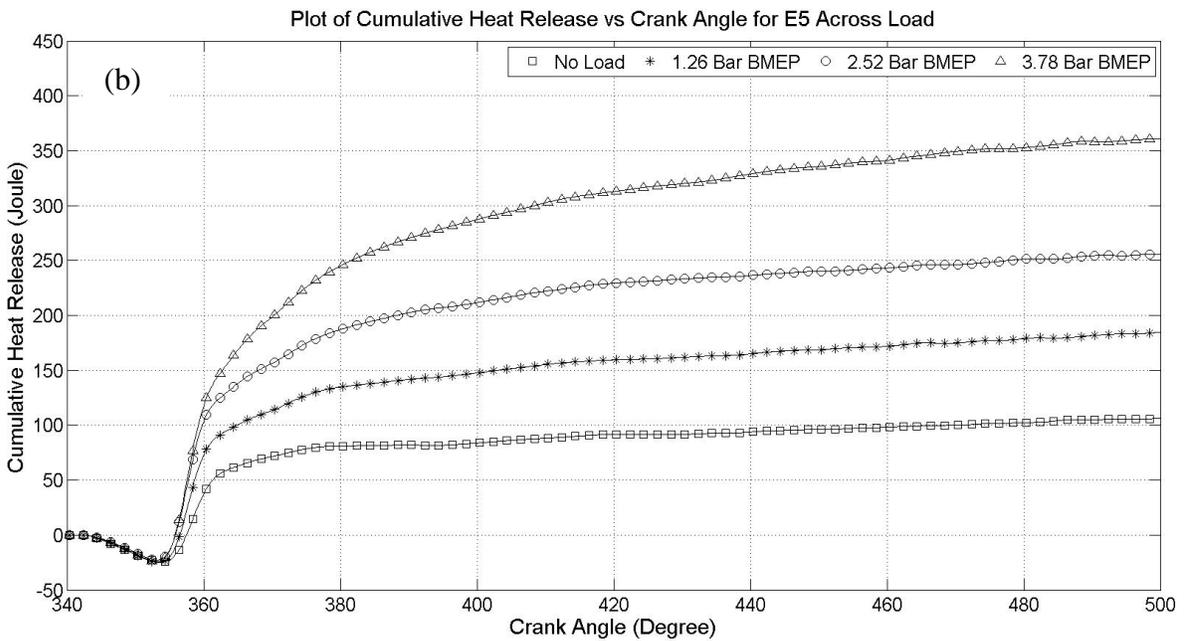
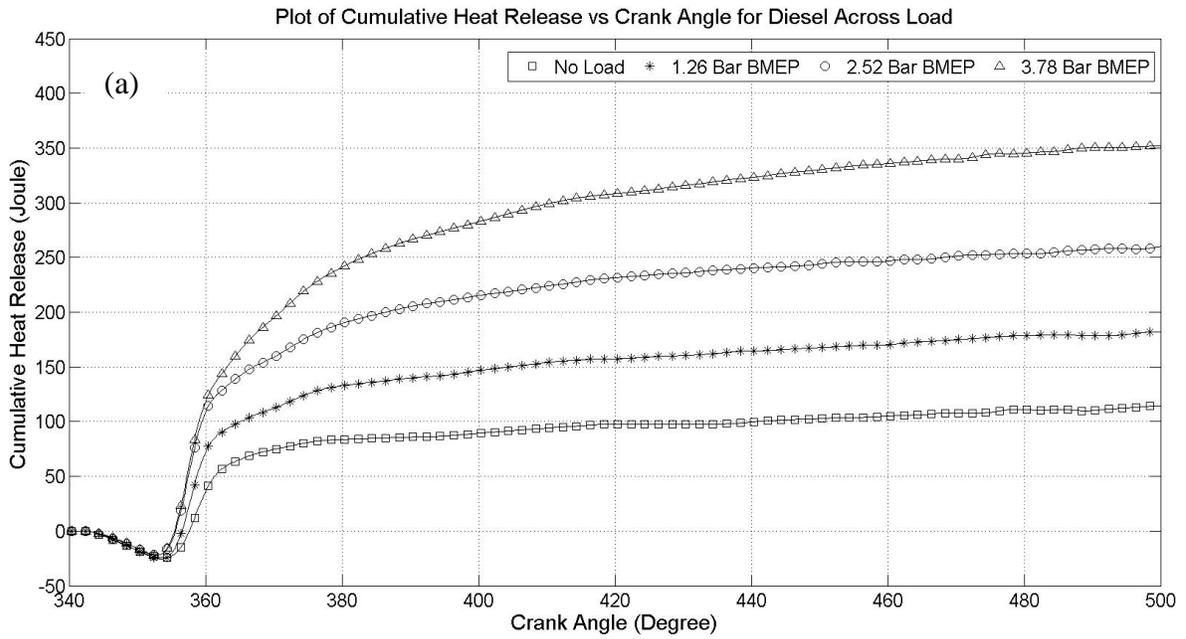


Figure 5.13: Cumulative heat release rate for (a) Diesel (b) E5 at different BMEPs

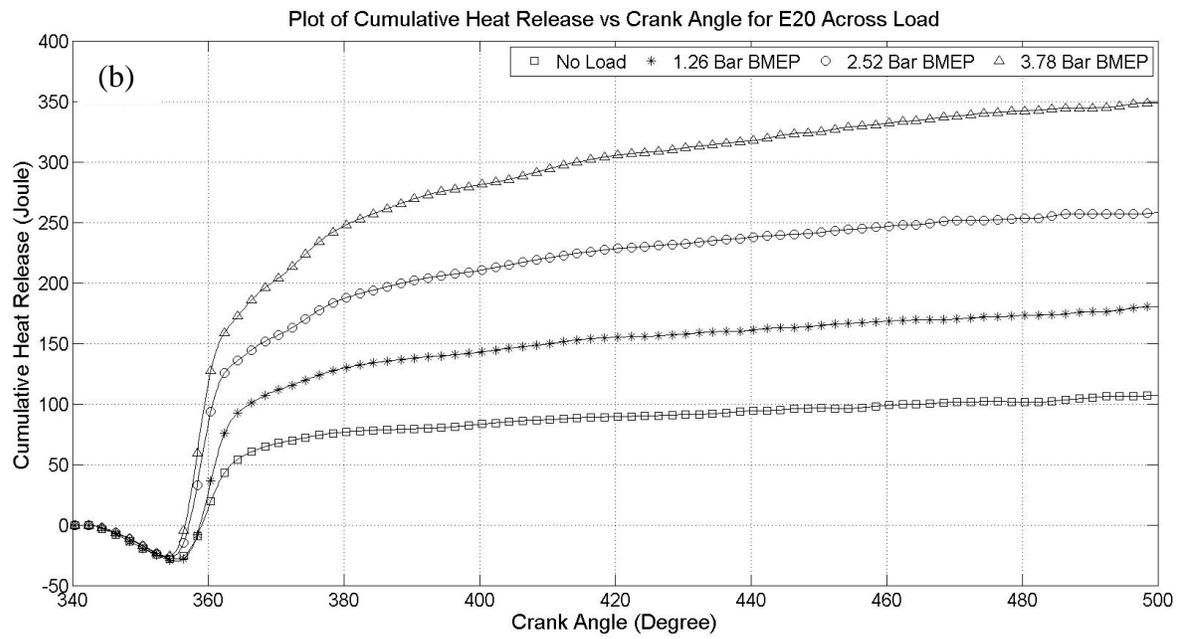
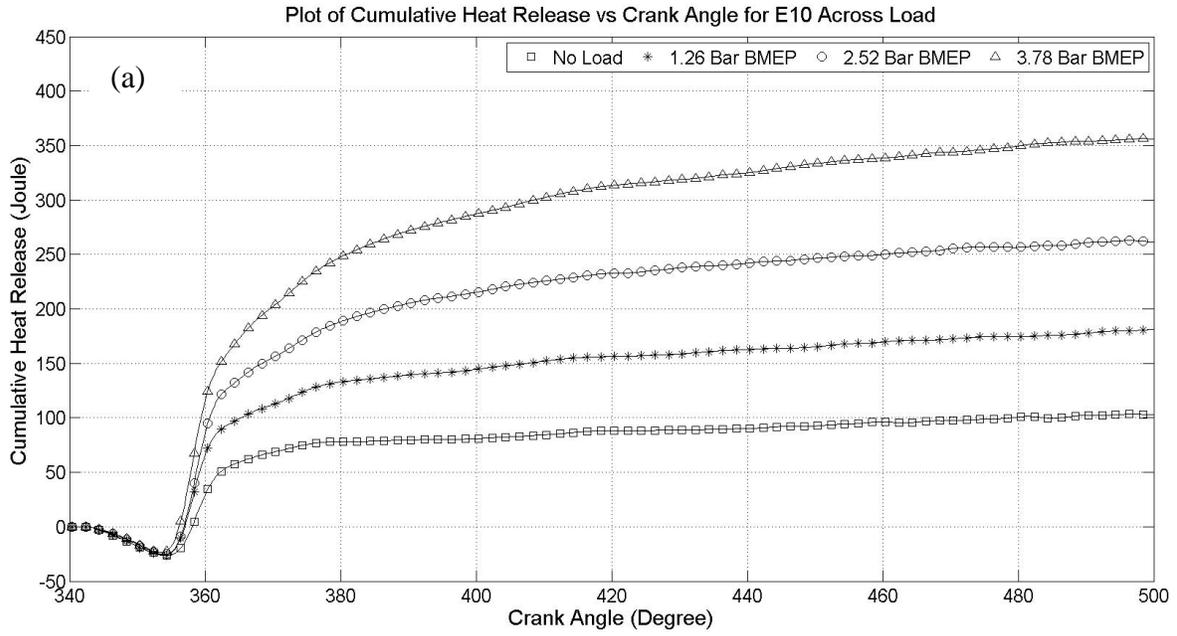


Figure 5.14: Cumulative heat release rate for (a) E10 (b) E20 at different BMEPs

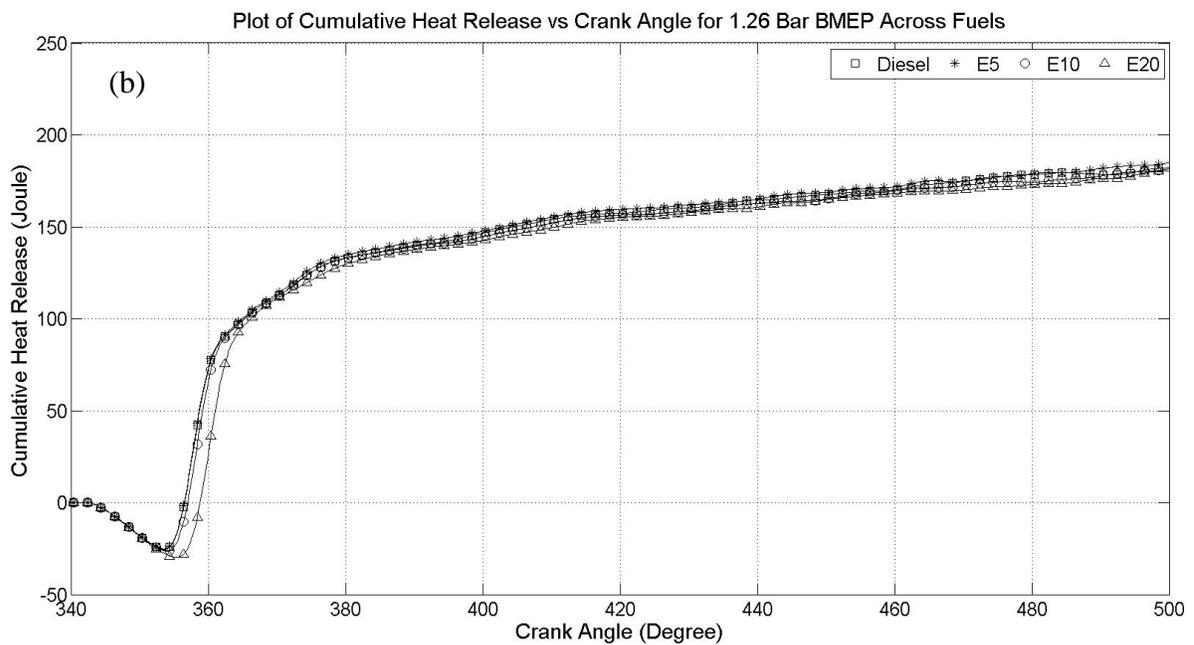
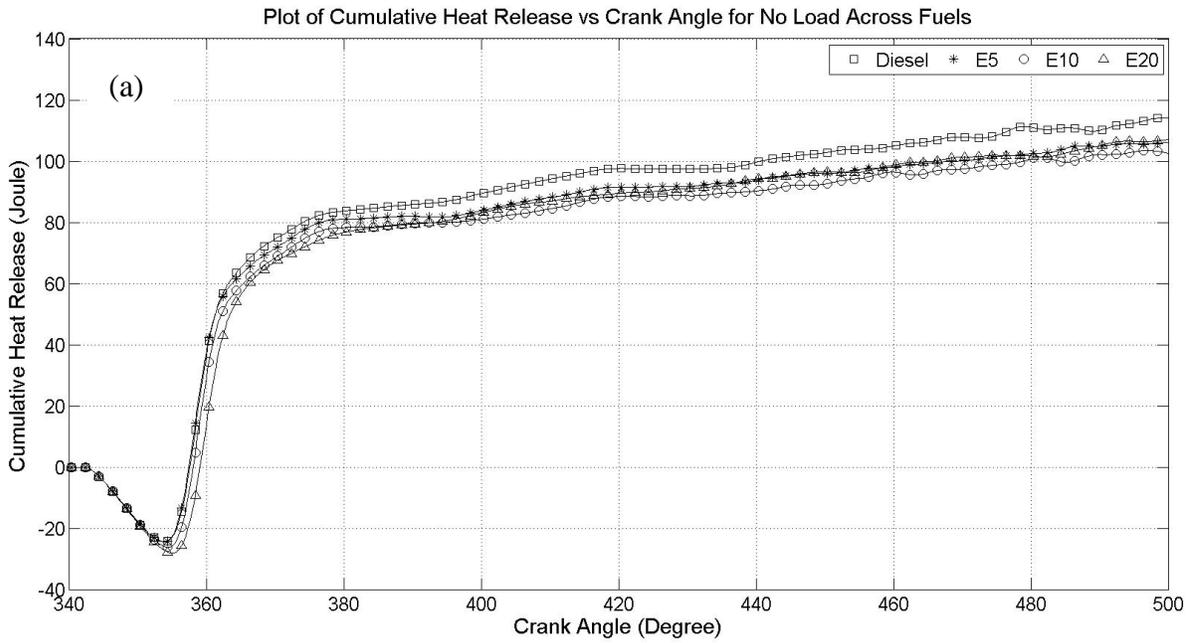


Figure 5.15: Cumulative heat release rate for (a) 0 bar (b) 1.26 bar BMEP for all fuels

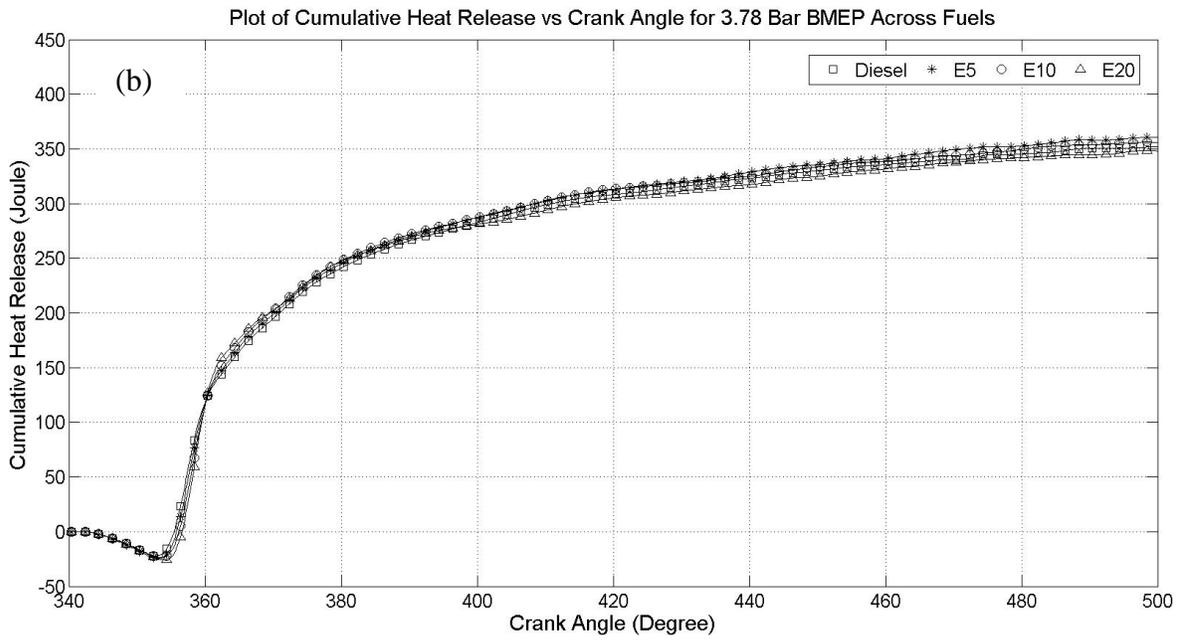
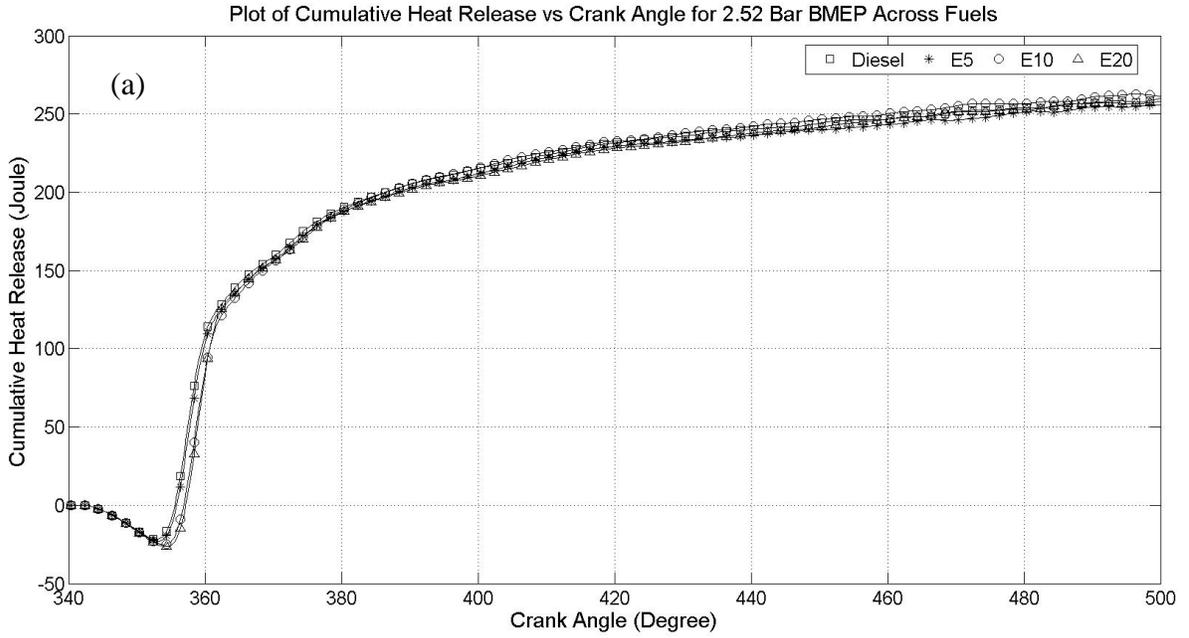


Figure 5.16: Cumulative heat release rate for (a) 2.52 bar (b) 3.78 bar BMEP for all fuels

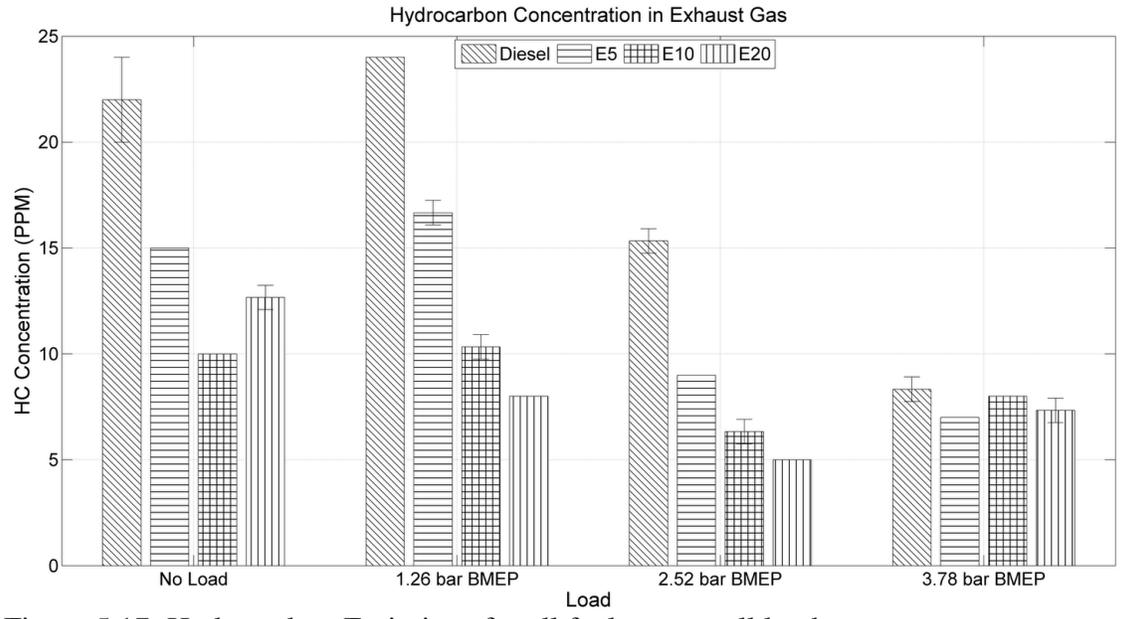


Figure 5.17: Hydrocarbon Emissions for all fuels across all loads

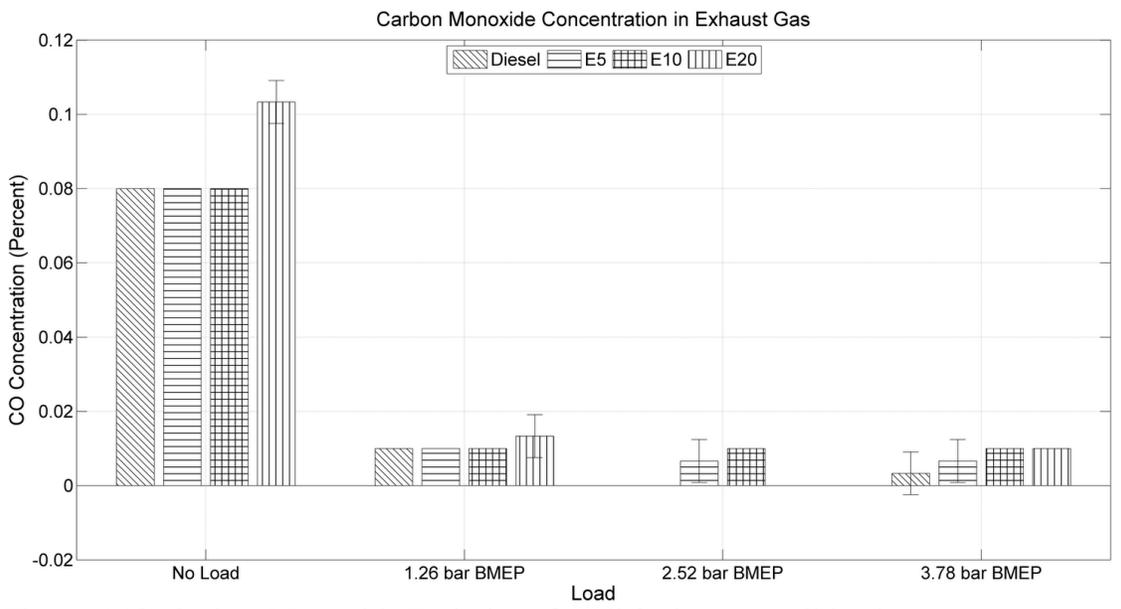


Figure 5.18: Carbon Monoxide Emissions for all fuels across all loads

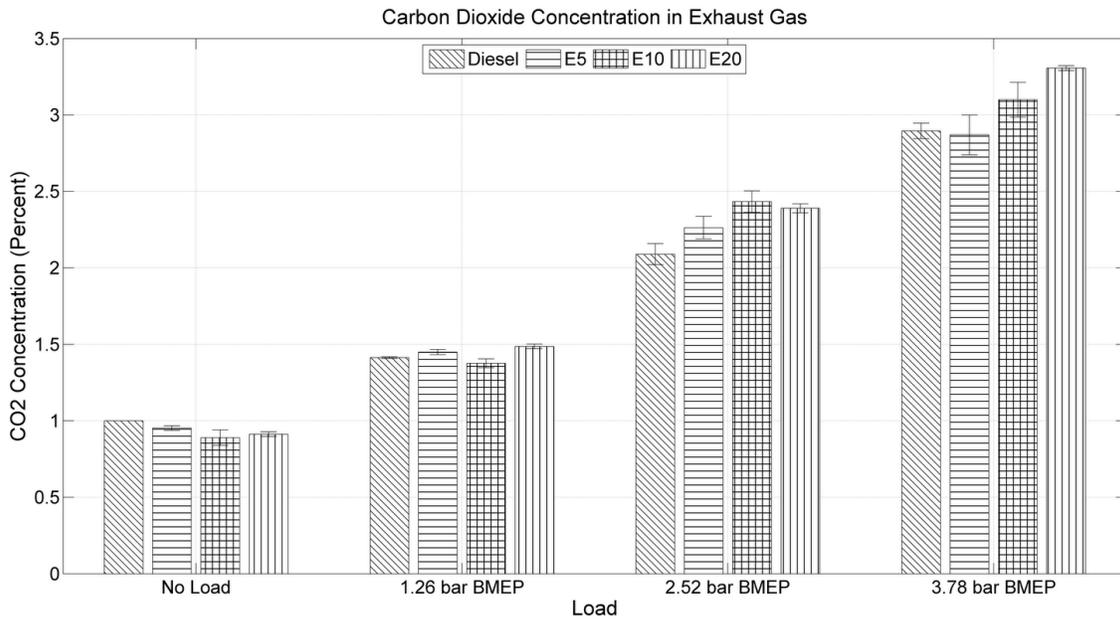


Figure 5.19: Carbon Dioxide Emissions for all fuels across all loads

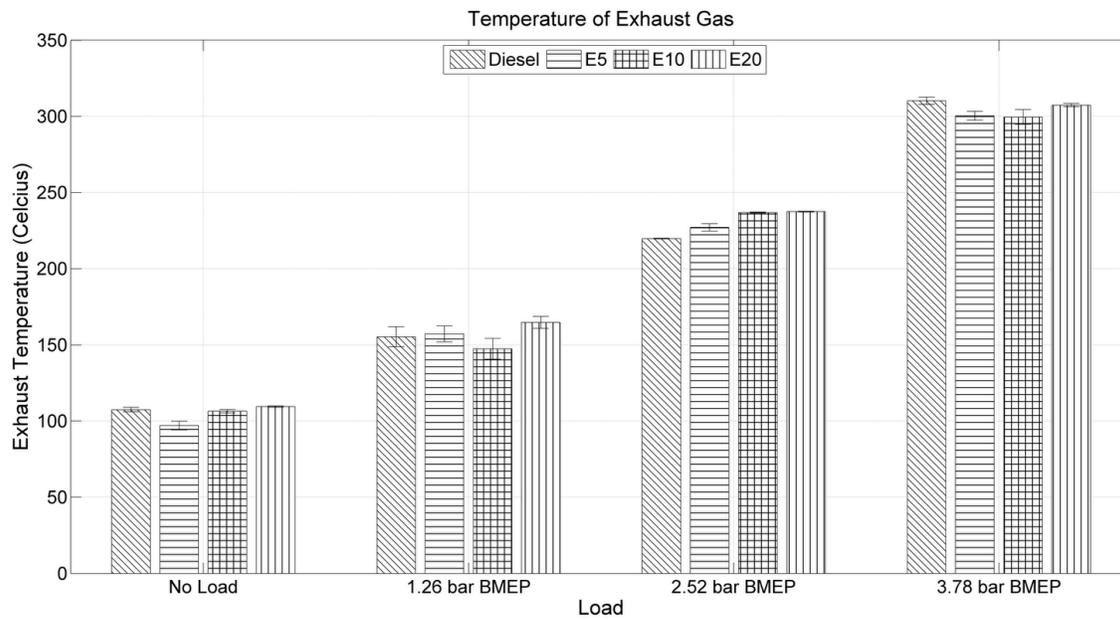


Figure 5.20: Exhaust Gas Temperature for all fuels across all loads

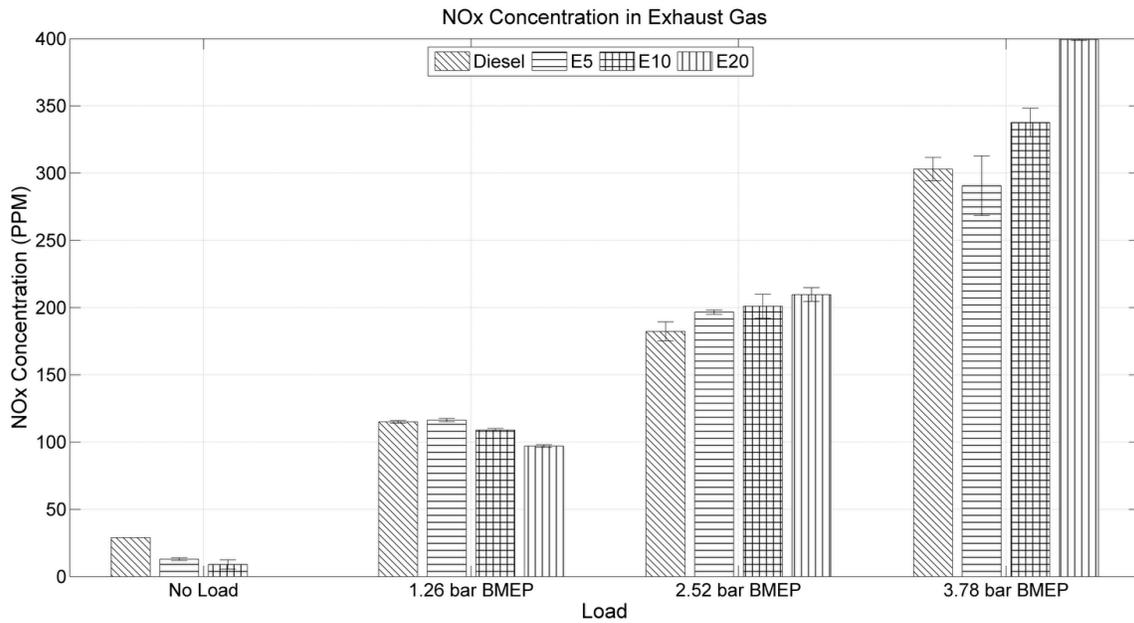


Figure 5.21: NO<sub>x</sub> emissions for all fuels across all loads

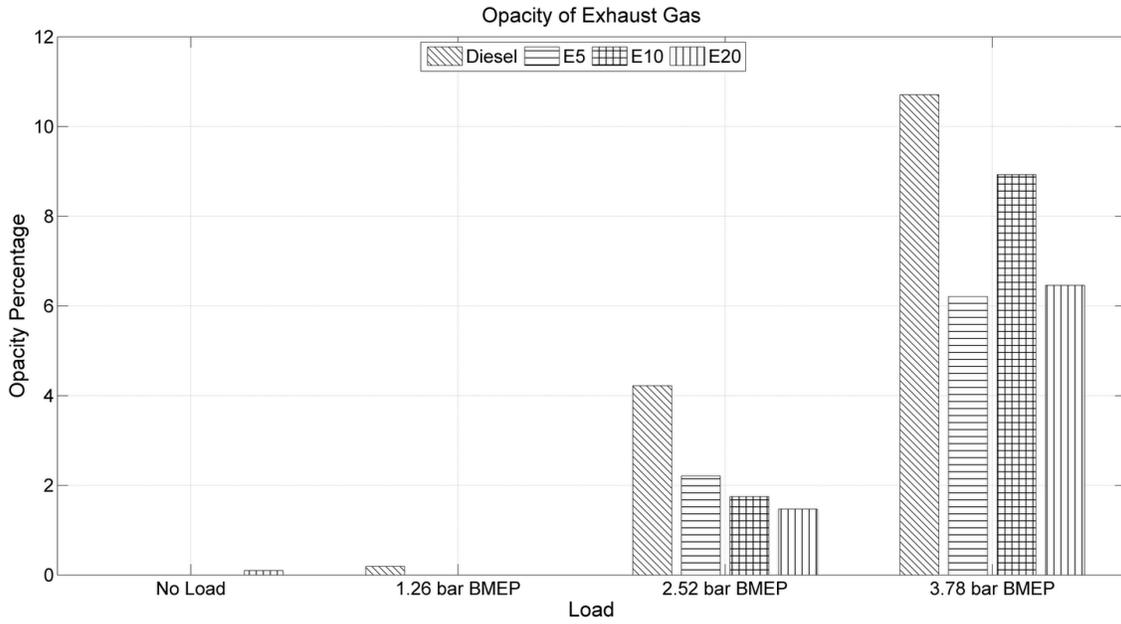


Figure 5.23: Smoke Opacity for all fuels across all loads

## CONCLUSION

Two bio-fuels were tested in this study with the aim of understanding their performance and emissions characteristics in internal combustion engines, specifically compression ignition engines and evaluating the possibility of replacing conventional fossil fuels on this regard. The choice of these parameters was to ensure sustainability, adequate performance and reduced pollutant emissions.

The first experiment used diesel extracts of bio-oil mixed in diesel as the fuel. Bio-oil was extracted from loblolly pine wood by pyrolysis and a technique of liquid-liquid extraction was used where diesel was the solvent. It was determined that the bio-oil extract mixtures' performance was comparable to that of diesel. The indicated work was slightly lower than that of diesel but at the same time the BSFC was also lower than diesel. The ignition delay exhibited by these fuels was longer and at the same time the peak cylinder pressure was lower than diesel. Lower HC and NO<sub>x</sub> emissions were observed which encourage the use of these fuels in light of strict emission norms. From all these observations, it can be concluded that diesel extracts of bio-oil in diesel is a viable alternative to diesel and can be further researched with different concentrations in future studies.

The second experiment used eugenol mixed with diesel. The aim was to understand the effect that eugenol had in modifying the combustion characteristics in isolation. Eugenol was a major component of the fuel used in the first experiment. Overall, the eugenol mixtures produced work outputs which were similar to diesel. The lower concentrations consumed lesser fuel than diesel. The peak cylinder pressure did not show much variation with respect

to diesel but tended to be a little higher in the case of mixtures with higher concentrations of eugenol. As before, the ignition delay was longer than diesel and overall more heat was released by these fuels. The HC and soot emissions were lower than diesel but in the case of  $\text{NO}_x$ , the observed levels were lower at low loads and higher at high loads, with reference to diesel emissions. All other emissions remained the same. These performance and emissions suggest that there is not much significant advantage in the use of eugenol mixed with diesel. However, more concentrations need to be tested in higher capacity engines to conclusively understand its behavior. Also other major hydrocarbon components of bio-oil can also be tested to understand their effect on combustion.

Both these fuels have been tested successfully and it appears that of the two, diesel extracts of bio-oil in diesel is a more viable option to replace current fossil fuels. Further experimentation with different concentrations is needed. Although eugenol has not shown much promise in this study, it must be tested further under more load conditions and at different concentrations. Also further testing under more practical conditions using higher capacity engines and more rigorous test cycles, will provide a more comprehensive understanding of these fuels.

## **FUTURE WORK**

Two fuels have been tested in this study. The diesel extracts of bio-oil in diesel mixture has shown a lot of promise in reducing emissions without compromising on performance. The eugenol mixture reduces some emission levels but only under certain load conditions and concentrations.

Further experimentation can be performed with different concentrations of extracts of bio-oil and also other kinds of bio-oil from different sources can also be explored. The effect of the addition of ash during the synthesis of bio-oil will be an interesting study.

The effect of eugenol mixtures in diesel can be more conclusively studied by testing a wider range of concentrations as well as under different load conditions as its behavior appears to vary a great deal depending on the load of the engine. Also other major organic components of bio-oil like guaiacol can be studied for their effect on the combustion characteristics.

With respect to the physical aspects of the engine, tests can be conducted using high power and high capacity engine under different speeds to better mimic real-life applications.

Since density and viscosity play a major role, pre-heating the fuel can be explored. An in-depth analysis of the fuels calorific value can also be undertaken. Such exercises will yield some interesting observations and deepen our knowledge about alternative, sustainable fuels.

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