ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Şafak YILDIZHAN

EFFECTS OF ENGINE PARAMETERS ON PERFORMANCE AND EMISSION CHARACTERISTICS OF A VARIABLE COMPRESSION RATIO ENGINE

DEPARTMENT OF AUTOMOTIVE ENGINEERING

ADANA-2017

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 09/01/2017

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ABSTRACT

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Supervisor : Assoc. Prof. Dr. Hasan SERİN
Year: 2017, Pages: 89
Jury : Assoc. Prof. Dr. Hasan SERİN
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This study investigates the performance and emission characteristics of a variable compression engine which is fueled with alternative fuels such as biodiesel and diesel-biodiesel blends. Camelina Sativa (false flax) oil which has variety of usage and has a potential of being feedstock for biodiesel production were used as alternative fuel. Also various common oils such as sunflower and canola oil were used as feedstocks for biodiesel production. Experimental study was conducted with a four stroke, single cylinder, naturally aspirated, multi fuel variable compression ratio engine by using diesel and alternative fuels. Experiments were performed at 1500 rpm and under partial load condition with three different compression ratios. Theoretical study was performed with the aid of Diesel RK software. Technical specifications of test engine were modelled using Diesel RK software and performance and emission characteristics were evaluated and compared with experimental results. The study showed that, increasing compression ratio significantly improves thermal efficiency and specific fuel consumption of the engine for all test fuels. The engine emitted lower carbon monoxide emission but higher carbon dioxide and nitrogen oxides (NO_x) emission when operated at higher compression ratios. Furthermore, biodiesel usage increased specific fuel consumption slightly. The engine emitted lower carbon monoxide emission but, higher nitrogen oxides (NO_x) emissions when biodiesel used as fuel.

Key Words: Compression ratio, Internal Combustion Engine, Biodiesel, Camelina Sativa, Diesel-RK

ÖZ

YÜKSEK LİSANS TEZİ

MOTOR PARAMETRELERİNİN SIKIŞTIRMA ORANI DEĞİŞEBİLİR BİR MOTORDA PERFORMANS VE EMİSYONLARA OLAN ETKİLERİ

Şafak YILDIZHAN

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
OTOMOTİV MÜHENDİSLİĞİ ANABİLİM DALI

Danışman : Doç. Dr. Hasan SERİN
Yıl: 2017, Sayfa: 89
Jüri : Doç.Dr. Hasan SERİN
: Prof.Dr. Kadir AYDIN
: Yrd.Doç.Dr. Erinç ULUDAMAR

Bu çalışmada biyodizel ve biyodizel-dizel karışımı gibi alternatif yakıtlarla çalıştırılan sıkıştırma oranı değiştirilebilir bir motorun performans ve emisyon karakteristikleri araştırılmıştır. Birçok kullanım alanı olan ve biyodizel üretim potansiyeline sahip olan Camelina Sativa (ketencik) yağı alternatif yakıt olarak kullanılmıştır. Ayrıca genel olarak kullanılan ayçiçek ve kanola yağları biyodizel üretimi için hammadde olarak kullanılmıştır. Deneysel çalışmalar, dört zamanlı, tek silindirli, çok yakıtlı, sıkıştırma oranı değiştirilebilir bir motorda dizel ve alternatif yakıtlar kullanılarak yapılmıştır. Deneyler 1500 devir (rpm) ve kısmi yük altında üç farklı sıkıştırma oranı ile yapılmıştır. Teorik çalışma Diesel RK yazılımı kullanılarak yapılmıştır. Test motorunun teknik özellikleri Diesel RK programında modellenmiş, performans ve emisyon karakteristikleri çıkarılarak deneysel sonuçlarla karşılaştırılmıştır. Çalışma, sıkıştırma oranının artırılmasının, bütün test yakıtları için motorun termik veriminin ve özgül yakıt tüketimini önemli ölçüde iyileştirdiğini göstermiştir. Motor yüksek sıkıştırma oranında çalıştığında, daha düşük karbon monoksit emisyonu verirken, daha yüksek karbon dioksit ve nitrjen oksit (NO_x) emisyonları vermiştir. Ayrıca, biyodizel kullanımı özgül yakıt tüketimini bir miktar arttırmıştır. Motor, biyodizel yakıt olarak kullanıldığında, daha az karbon monoksit emisyonu verirken, daha yüksek nitrojen oksit (NO_x) emisyonu vermiştir.

Anahtar Kelimeler: Sıkıştırma Oranı,, İçten Yanmalı Motorlar, Biyodizel, Camelina Sativa, Diesel-RK

GENİŞLETİLMİŞ ÖZET

Günümüzde içten yanmalı motorlar taşıma, ulaşım ve endüstüride yaygın olarak termik makinelerdir. İçten yanmalı motorlar yakıt içerisindeki kimyasal enerjiyi oksitleyerek (yakarak) açığa çıkarır ve bu enerjiyi kinetik enerjiye çevirirler. Ancak, yakıt olarak kullanılan fosil kaynaklı dizel ve benzeri yakıt rezervleri bilindiği üzere hızlı bir şekilde tükenmektedir. Aynı zamanda fosil kaynaklı yakıtların artan maliyetleri ve çevresel etmenlerden dolayı petrol kaynaklı yakıtlara alternative arayışları araştırmacıları bu alanda çalışmalar yapmaya zorlamaktadır. Petrol kaynaklı yakıtlara alternatif olarak kullanılacak yakıtlarda aranan başlıca özellikler, yenilenebilir, sürdürebilir ve çevreyi daha az kirletme özelliğine sahip olmasıdır. Günümüzde biyodizel, biyoetanol, alkol, hidrojen, vs. gibi birçok alternative yakıt içten yanmalı motorlarda alternatif olarak kullanılmaktadır.

Dizel (sıkıştırma patlamalı) motorlar yüksek tork üretme kabiliyeti ve benzinli motorlara göre daha yüksek verimlilik ve daha az özgül yakıt tüketiminden dolayı özellikle taşımacılık ve ağır iş makinelerinde en çok kullanılan termik makinelerdir. Dizel motorlarda yakıt olarak kullanılan petrol kaynaklı motorin yerine alternatif enerji kaynakları arayışı tüm dünyada yayılmıştır. Dizel motorlar Rudolf Diesel tarafından ilk lansmanı yapıldığında bitkisel mısır yağı ile çalışıyordu. Zaman içerisindeki gelişmeyle dizel yakıtlar bu motorda kullanılmaya başlanıldı. Ancak günümüze en çok dikkat çeken alternatif yakıtlardan biri de bitkisel, hayvansal veya atık yağların esterifikasyonu ile üretilen biyodizel adı verilen yakıtlardır. Alternatif yakıt arayışları ile beraber mevcut motorların daha verimli çalışması ve çevreye daha az zararlı egzoz emisyonu salınımı için motorun çalışma parametleri üzerinde de birçok araştırma yapılmıştır.

Dizel motorlar dizel çevrimi prensibine göre çalışırlar. Teorik olarak incelendiğinde dizel motorların termik verimliliği benzinli motorlardan yüksektir. Buının temel sebebi, dizel motorlar benzinli motorlardan daha yüksek sıkıştırma oranı ile çalışırlar. Dizel çevrimi teorik olarak incelendiği zaman termik verimi etkileyen en önemli faktör sıkıştırma oranıdır.

Bu çalışmada biyodizel ve biyodizel-dizel karışımı gibi alternatif yakıtlarla çalıştırılan sıkıştırma oranı değiştirilebilir bir motorun performans ve emisyon karakteristikleri araştırılmıştır. Birçok kullanım alanı olan ve biyodizel üretim potansiyeline sahip olan Camelina Sativa (ketencik) yağı alternatif yakıt olarak kullanılmıştır. Ayrıca genel olarak kullanılan ayçiçek ve kanola yağları biyodizel üretimi için hammadde olarak kullanılmıştır. Deneysel çalışmalar, dört zamanlı, tek silindirli, çok yakıtlı, sıkıştırma oranı değiştirilebilir bir motorda dizel ve alternatif yakıtlar kullanılarak yapılmıştır. Deneyler 1500 devir (rpm) ve kısmi yük altında üç farklı sıkıştırma oranı ile yapılmıştır. Aynı zamanda deneysel olarak elde edilen veriler Diesel-RK yazılımıyla modellenerek deneysel verilerle karşılaştırılmıştır.

Biyodizel numuneleri, transesterifikasyon reaksiyonu adı verilen kimyasal bir metodla hazırlanmıştır. Biyodizel üretiminde kullanılan yağın hacimsel oalrak %20 oranında methanol ve kütlesel olarak %0,5 oranında sodyum hidroksit kullanılmıştır. Bu reaksiyonda sodium hidroksit katalizör olarak kullanılmıştır. Biyodizel yakıtlar, Çukurova Üniversitesi Otomotiv Mühendisliği Laboratuvarında üretilmiştir. Üretimi yapılacak olan yağ önce 65 ^{o}C’ye ısıtılmıştır ve öncesinde hazırlanan ve metoksit adı verilen alkol-katalist karışımıyla 90 dakika boyunca karıştırılarak sabit sıcaklıkta reaksiyona sokulmuştur. Reaksiyon sonrasında ham biyodizel-gliserin karışımı ayırma hunilerine alınarak 8 saat boyunca bekletilmiştir. Bekletme sırasında yoğunluk farkından dolayı ham biyodizel üstte kalmış gliserin fazı ise dibe çökmüştür. Ayırma işlemi tamamlandıktan biyodizel ılık suyla 3-4 kez yıkanmış ve sonrasında 105 ^{o}C’de bir saat süresince kurutulmuştur. Son olarak biyodizel filtrelenerek rafine edilmiştir. Hazırlanan biyodizeller ve bu biyodizellerin dizel yakıtı ile %20 oranında (B20) karışımlarının bazı önemli yakıt özellikleri test edilmiş, sonrasında ise motor performans ve emisyon testlerine tabi tutulmuştur.

Deneysel çalışmalar sıkıştırma oranı değiştirilebilir bir motorda (Kirloskar Oil Engines- 240) üç farklı sıkıştırma oranı ile (12:1, 14:1, ve 16:1) ve 7 farklı yakıt ile yapılmıştır. Her deneyden önce motor stabil çalışma koşullarına getirilerek testler yapılmıştır. Deneylerde, termik verim, özgül yakıt tüketimi, silindir içi basınç, egzoz gaz sıcaklığı,karbon monoksit, karbon dioksit, azot oksit gibi önemli performans ve emisyon karakteristikleri incelenmiş ve sonrasında Diesel-RK yazılımı yardmıyka modellenerek karışılaştırma yapılmıştır.

Yapılan yakıt özellikleri testleri sonucunda, deneylerde kullanılan tüm yakıtların EN ve ASTM standartları içerisinde olduğu görülmüştür. Ketencik yağından elde edilen biyodizelin yoğunluğu ve viskositesi dizel yakıta göre bir miktar yüksek çıkmıştır. Bundan dolayı ketencik yağı biyodizeli-dizel karışımın yoğunluğu ve viskositesi de dizel yakıtına göre yükselmiştir. Ketencik yağı biyodizelinin ısıl değeri dizel yakıta göre %14,8 daha düşük bulunmuştur. Diğer önemli bir özellik olarak soğuk filtre tıkama noktası is -10 ^oC olarak bulunmuştur. Bu değer palm, pamuk biyodizeli gibi yakıtlarla karşılaştırıldığında ketencik yağının önemli bir avantajıdır. Parlama noktası testlerinde de tüm biyodizel yakıtların parlama noktası dizel yakıttan daha yüksek çıkmıştır.

Deneysel çalışmada dizel, ketencik yağı ayçiçek yağı ve kanola yağı biyodizelleri ile bu biyodizellerin dizel yakıtlar ile %20 oranında (B20) karışımlarının yanma, performans ve emisyon karakteristikleri incelenmiştir. Deneyler sabit devir (1500 dev/dak), kısmı yük altında (%60 yük) ve üç farklı sıkıştırma oranında (12:1, 14:1 ve 16:1) yapılmıştır. Deneysel çalışmaların sonuçlarının hata analizi yapılarak yükleme ve devir koşullarının deneysel olarak hata oranı bulunmuştur. Motorun tork (yüklemeye bağlı) sonuçlarına göre deneysel ortalama hata ±0,05389 Nm olarak bulunmuştur. Devire göre yapılan hata analizinde ise ortalama hata ±3,3519 dev/dak olarak bulunmuştur.

Yakıtların silindir içi basınç sonuçları incelendiğinde sıkıştırma oranı artışının maksimum silindir içi basıncı önemli ölçüde arttırdığı gözlemlenmiştir. Yüksek sıkıştırma oranı ile yapılan deneylerde yanma gecikmesi azalmış ve silindir içi basıncın maksimum noktası üst ölü noktaya yaklaşmıştır. Deneysel çalışmalarda sıkıştırma oranı artışının yanmayı önemli ölçüde iyileştirdiği görülmüştür. Biyodizel kullanımı ile maksimum silindir basıncı dizel yakıta kıyasla bir miktar düşmüştür. Bu, biyodizellerin düşük ısıl değerinden dolayı beklenen bir olgudur.

İçten yanmalı motorlarda termik verim elde edilen gücün motora verilen kimyasal enerjiye oranı olarak tanımlanabilir. Isıl verim yakıtların yanması ve motor karakteristiği ile doğrudan ilişkilidir. Motorlarda termik verimi etkileyen en önemli faktörlerden birisi ise sıkıştırma oranıdır. Sıkıştırma oranının arttırılmasıyla termik verimin tüm yakıtlar için önemli ölçüde yükseldiği deneyler sonucunda görülmüştür. Sıkıştırma oranı 12:1'den 16:1'e yükseldiği zaman dizel yakıt için termik verim %5,16 iyileşmiştir. Ketencik yağı biyodizeli için ise bu oran %13,23'tür. Motorda termik verimin yükselmesi yakıt tüketimini olumlu etkilemiştir. Özgül yakıt tüketimi birim gücü elde etmek için harcanan yakıt miktarı olarak tanımlanabilir. Sıkıştırma oranının artması tüm yakıtlar için özgül yakıt tüketimini azaltmıştır. Yakıt tüketiminin azalması hem ekonomik anlamda hem de daha az yakıt kullanılacağından çevresellik ve sürdürülebilirlik açısından çok önemlidir. Sıkıştırma oranının 12:1'den 16:1'e yükseltilmesiyle dizel yakıtının özgül yakıt tüketimi %13,37 oranında azalmıştır. Bu oran ketencik yağı biyodizeli için ise %9,13 olarak bulunmuştur. Sıkıştırma oranının artmasıyla termik verimde maksimum artış %13,37 oranıyla ketencik yağı biyodizelinde gözlenmiştir. Özgül yakıt tüketimendeki maksimum iyileşme ise %13,45 oranıyla ayçiçek biyodizeli-dizel karışımı (B20) yakıtında gözlenmiştir.

Motorlar için diğer önemli bir ölçüm ise egzoz gaz sıcaklığıdır. Yapılan deneylerde sıkıştırma oranın artmasıyla tüm yakıtların egzoz gaz sıcaklıklarının yükseldiği gözlemlenmiştir. Egzoz gaz sıcaklığı silindir içi yanma karakteristikleri hakkında önemli ipuçları vermektedir. Egzoz gaz sıcaklığı aynı zamanda özellikle azot oksit emisyonlarını direk etkileyen faktörlerin başında gelmektedir.

Çalışmada yapılan egzoz emisyon ölçümleri neticesinde karbon monoksit emisyonlarının yüksek sıkıştıma oranında daha az salındığını tespit edilmiştir.

Yüksek sıkıştırma oranı ile yanma iyileşmesi gerçekleşmiş ve buna bağlı olarak daha az karbon monoksit (CO) emisyonu salınmıştır. Aynı zamanda biyodizel kullanımı da dizel yakıta kıyasla daha az karbon monoksit emisyonu vermiştir. Bunun temel sebebi biyodizel yakıtların kimyal yapısında bulunan ekstra oksijen içeriğidir. Buna karşın karbon dioksit (CO_2) emisyonları sıkıştırma oranı artışı ile önemli ölçüde artmıştır. Aynı zamanda biyodizel kullanımı da CO_2 emisyonlarını önemli ölçüde arttırmıştır. Motorlarda çevreye en çok zarar veren emisyonlardan biri de azot oksit (NO_x) emisyonlarıdır. NO_x emisyonları silindir içi yanma sıcaklığı ile doğrudan ilişkilidir. Sıkıştırma oranının yükseltilmesiyle silindir içi basınç ve sıcaklık arttığından NO_x emisyonlarında bütün test yakıtları için artış gözlenmiştir. Ayrıca biyodizel kullanımı da daha yüksek yanma sıcaklığı ve ekstra oksijen içeriğinden dolayı NO_x emisyonlarını arttırmıştır.

Çalışmada kullanılan test motoru ve diğer test yakıtları Diesel-RK simülasyon yazılımı aracılığıyla modellenmiştir. Modellemede deneysel çalışmada olduğu gibi üç farklı sıkıştırma oranı kullanılmıştır. Teorik çalışma yapılırken deneysel motorun geometric ve yapısal özellikleri ile kullanılan yakıtların yoğunluk, viskosite, ısıl değer vb. özelliklerinden faydalanılmıştır. Teorik modelleme sonuçları deneysel verilerle kıyaslanmıştır. Modelleme sonucunda deneysel ve teorik sonuçların aynı eğilim içerisinde olduğu görülmüştür. Bu eğilim ile deneysel ve teorik çalışmalar birbirlerini doğrulamıştır.

Sonuç olarak, deneysel ve teorik çalışmaların değerlendirilmesiyle sıkıştırma oranı arttırılmasının motorun yanma, performans verilerini önemli ölçüde iyileştirdiği görülmüştür. Aynı zamanda sıkıştırma oranının yükseltilmesinin CO emisyonlarını iyileştirirken CO_2 and NO_x emsiyonlarının artmasına neden olduğu bulunmuştur. Çalışmanın odak noktalarından birisi olan ketencik yağının ise biyodizel hammaddesi olarak kullanılabileceği, ketencik yağından üretilen biyodizel yakıtının özelliklerinin Amerikan ve Avrupa Biyodizel Standartlarına uygun olduğu deneysel sonuçlarla gösterilmiştir. Motor deneyleri de ketencik yağı biyodizelinin dizel motorlarda alternatif bir yakıt olarak kullanılabileceğini göstermiştir.

ACKNOWLEDGEMENTS

First of all, I would like to thank to my supervisor, Assoc. Prof. Dr. Hasan SERİN, for his support and encouragement throughout preparation of this thesis.

I sincerely thank Prof. Dr. Kadir AYDIN and Assoc. Prof. Dr. Mustafa ÖZCANLI for sharing his knowledge and valuable time for this work.

I would like to heartfelt thank Erinç ULUDAMAR and Erdi TOSUN, for their support and effective advices.

I would like to thank to all Automotive Engineering Department academic personals Prof. Dr. Ali KESKİN, Assoc. Prof. Dr. Alper Yılmaz, Assoc. Prof. Dr Abdülkadir YAŞAR, Assoc. Prof. Dr. Mehmet BİLGİLİ, Asist. Prof. Dr. M. Atakan AKAR, Asst. Prof. Dr. Tayfun ÖZGÜR and Specialist Dr. Ceyla ÖZGÜR.

I would like to thank all my research assistant friends at Automotive Engineering Laboratories of Çukurova University and all staff of Automotive Engineering Department at Çukurova University for their continuous support and motivation.

Last but not least, I would like to thank my fiancee, Zehra DAĞYAR and my parents, Coşkun YILDIZHAN, Tülay YILDIZHAN, and my sister Sultan YILDIZHAN. I wouldn’t have succeeded my thesis without their support and encouragement.

CONTENTS **PAGE**

LIST OF TABLES **PAGE**

LIST OF FIGURES **PAGE**

LIST OF ABBREVIATIONS AND NOMENCLATURE

η_{th}	:	Thermal Efficiency
η_{v}	:	Volumetric Efficiency
1D	:	One Dimension
2D	:	Two Dimension
A	:	Area
ASTM	:	American Society of the International Association for Testing and Materials
BDC	:	Bottom Dead Center
BMEP	:	Brake Mean Effective Pressure
BTHE	:	Brake Thermal Efficiency
c	:	Specific heat
CB100	:	Canola Biodiesel (%100)
CB20	:	Canola Biodiesel (%20)
CFPP	:	Cold Filter Plugging Point
CM	:	Centimetres
CO	:	Carbon Monoxide
CO_2	:	Carbon Dioxide
CR	:	Compression Ratio
D	:	Diesel
EGT	:	Exhaust Gas Temperature
EN	:	European Committee for Standardization
EU	:	European Union
FB100	:	False Flax Biodiesel (%100)
FB20	:	False Flax Biodiesel (%20)
G	:	Gram
GHG	:	Green House Gas

HC	:	Hydrocarbons
IMEP	:	Indicated Mean Effective Pressure
IT	:	Injection Timing
L	:	Stroke
MB	:	Microalgea Biodiesel
N	:	Engine Speed
NO	:	Nitrogen Oxide
NO_2	:	Nitrogen Dioxide
NO_x	:	Nitrogen Oxide
NO_x	:	Nitrogen Oxides
P	:	Pressure
PM	:	Particulate matter
POME	:	Palm Oil Methyl Ester
PPM	:	Particulate Per Million
Q	:	Heat
R	:	Compression Ratio
RPM	:	Revolution Per Minute
S	:	Entropy
SB100	:	Sunflower Biodiesel (%100)
SB20	:	Sunflower Biodiesel (%20)
SFC	:	Specific Fuel Consumption
SO_2	:	Sulphur dioxide
T	:	Temperature
TDC	:	Top Dead Center
V	:	Volume
V_c	:	Clearence Volume
VCR	:	Variable Compression Ratio
V_s	:	Swept Volume

α	:	Cut-off ratio
γ	:	Ratio of specific heats (c_p/c_v)

1. INTRODUCTION

The major part of all energy consumed in the world is supplied from the fossil based substances such as petroleum, coal and natural gas. But as it is widely known, these energy sources are exhausting rapidly. Therefore, alternative sources of renewable and sustainable energy researches have gained great importance. Also, some other problems such as, rising price of petroleum products, air pollution and global warming could be solved with renewable energy investigations. (Demirbas, 2005).

It is a widely known fact which transportation of people and goods is provided by using fossil fuels which are gasoline, diesel fuel, liquefied petroleum gas, etc. With the decrement of potential fossil reserves, the need of new technology for producing new substitutions in order to sustain the energy demand of modern human life is increasing. There are several causes for biofuels to be paid regard to consistent technologies by both industrialized and developing countries. These consist of environmental problems, energy security issues, savings of foreign exchange, and concerns of socioeconomic for all countries. Biofuels getting more attention recently caused by its environmental compensation and sustainability (Balat, 2009; Humbad et al., 2009; Dincer, 2008; Hacisaligoglu, 2009; Demirbas, 2009a; Demirbas, 2009b)

The diesel engines are dominant tool in the sector of commercial transportation and machinery for agricultural because of their operation convenience and relatively high fuel efficiency. The fuel consumption of the diesel engines is lower than gasoline engines which makes diesel engine economically more feasible. Depending on the depletion of petroleum based products and their elevated cost, efforts focus to develop potential alternative fuels particularly, to the conventional diesel fuel for completely or partial replacement. The facts that the vegetable oils are rewarding fuels because of their properties are alike to petroleum diesel and are produced easily and renewably from different feedstocks (Ramadhas et. al., 2005).

The feasibility of an alternative fuel usage instead of petroleum fuel basically depends on being economical, environment friendly, renewable and easily accessible. The most widely known alternative fuel to diesel fuel could be called as biodiesel. Biodiesel usage may improve some of the emissions levels such as carbon monoxide and unburned hydrocarbons and deteriorate other such as oxides of nitrogen. However, for interpreting the incidences of biodiesel usage several other factors should be taken into account such as feedstock (raw material), accessibility, driving cycle, cost, vehicle technology, sustainability etc. Usage of biodiesel will let to be set a balance between agriculture, economic issues and the environmental problems (Demirbas, 2007).

The advantages of biofuels compared to traditional fuels include higher energy security, lower environmental damage, locally availability, and socioeconomic objects related with the rural sector. Furthermore, biofuel production technology is linked to developing and also to industrialized countries. Thus, the market share of renewable fuels in the automotive sector is expected to increase progressively. Biofuels are sustainable due to being renewable and available in the world's most parts. Policy- makers are supposed to focus on the effects of the transition to biofuel economy. The sustainable development concept concretizes the idea of and the balance between social, environmental, and economic, concerns and the inter-linkage (Balat, 2007a; Demirbas, 2008b; Demirbas, 2009b).

The term biofuel is called to solid (bio-char) mass, liquid (ethanol, vegetable oil and biodiesel) or gaseous (biogas, bio syngas and bio hydrogen) energy sources which are mostly produced from biomass (Kong et al., 2008; Balat, 2008; Balat, 2009). Biofuels production costs depend on raw material, production process, production scale and local variables. The raw material (feedstock) used in biofuel production is the major part of the overall production cost. The raw material should be competitive for biofuel production, especially oil-derived biofuels should be considered due to food industry needs. (Demirbas, 2008c).

Over one century ago, Rudolf Diesel presented his engine with peanut oil (Shay, 1993). With the cheap petroleum derived oil fractions diesel fuel refined and contributed the evaluation of the diesel engines. In the 1930s and 1940s vegetable oils were used instead of diesel fuels in some cases, but usually only for emergency situations. Recently, the high price of the petroleum products, limited reserves and environmental concerns leaded to production of biodiesel form vegetable oils and animal fats. Progressively increasing use of petroleum products will increase the local air pollution and worsen the global warming issues affected by CO_2 (Shay, 1993). Especially, pollutants emissions underground mines which are in the closed environments, biodiesel fuel usage can decrease the level of dangerous pollutants and the level of potential or probable carcinogens (Krawczyk, 1996).

Over the past decades, environmental issues caused by the widespread usage of fossil based fuels have elevated the awareness for less toxic, emitting lower emissions, cleaner and alternative technologies for production all over the industrialized world. Currently, sector of transportation in the European Union (EU) spends more than 30 % of the total energy consumption and mainly this energy is supplied from the usage of fossil based which are widely known as sources of harmful emissions, pollutants and are considered to be unsustainable due to their depleting resources (European Commission and Eurostat, 2013).

By consenting many instruments and target-oriented regulations, policy makers are supporting the usage of bio based fuels like biodiesel in European countries. Known as the 2020 strategy, a major European Union policy package (European Parliament, 2009) was established a mandatory aim of at least 10 % of the energy consumption in the sector of transportation to increase from renewable sources in 2020, in 2009.

Researchers are looking forward to new raw materials, especially non-edible materials for biodiesel production (Anwar et al., 2010; Balusamy and Marappan, 2010; Altun, 2011). Many vegetable oils such as pomace oil (Caynak et al., 2009), soybean oil (Canakci and Van Gerpen, 2003b), castor oil (Ozcanli et al., 2011b), tobacco seed oil (Usta, 2005), safflower seed oil (Hamamci et al., 2011), terebinth oil (Ozcanli et al., 2011a), tea seed oil (Serin et al., 2013) and karanja oil (Srivastava and Verma, 2008) etc. have been used for producing biodiesel fuel. Alcohols which are considered as alternative fuels for diesel engines in general are used as additives for diesel and blended fuels in compression ignition engines (Yilmaz and Vigil, 2014). It is not a new development that usage of alcohols in the internal combustion engines. Alcohol fuels have been used discontinuously in the engines since their invention. The first usage of ethanol commercially as fuel started when the Ford automobile company manufactured Henry Ford's Model T to use corn alcohol, called ethanol in 1908 (Imran et al., 2013). Alcohol fuels contain extra oxygen unlike diesel and gasoline. Blending petroleum products with alcohols provides the fuel to burn out more completely depending on the extra oxygen presence, which improves the efficiency of combustion and decrases the air pollution. 10% ethanol blended gasoline usage can decrease gas emissions which has greenhouse gas effect (Surisetty et al., 2011). The alcohol presence in fuel may show corrosive effect to metallic parts used in the fuel system components caused by elevated water content in the fuel composition and slightly because of the organic acids which are produced in commercial oxygenates. Other significant disadvantages of alcohol usage are vapour lock because of low boiling points and high vapour pressures (Karabektas and Hosoz, 2009). Alcohol usage in compression ignition engines has some advantages and disadvantages. For improving fuel quality alcohols in general, are used as additives for diesel and biodiesel fuels.

Simulation studies of internal combustion engines are effective processes since simulation tools saves cost and time considerably comparing to actual experiments. Simulation tools predict the performance, combustion and emission characteristics of created models. Simulation tools work on theoretical equations and aims to converge the actual processes. However, the actual process of running an internal combustion is too complex for completely modelling. Therefore, simulation tools give results with acceptable errors.

Diesel engines are widely used as transportation tools and energy converters (generators) all around the world. Higher thermal efficiency of diesel engines than petrol engines made more attractive diesel engines compared to petrol engines. Thermal efficiency of diesel engines depends on three parameters (compression ratio, cut-off ratio and adiabatic heat constant) theoretically.

Renewable energy sources can be a feasible alternative to petroleum based fossil fuels which are depleting rapidly. Recently, biofuels and biomass are started to be considered all over the world as alternative energy sources because of their significant advantages such as being eco-friendly and biodegradable (Saidur et al., 2012). But, current compression ignition engines are designed to operate with diesel fuel. So, engines are supposed to be modified to use alternative fuels for optimizing the operating conditions.

According to previous studies, Camelina sativa (false flax) has a potential of being a renewable and sustainable oilseed crop for biodiesel production (Yang et al., 2016). Camelina sativa belongs to Brassicaceae family (Krohn and Fripp, 2012; Zubr, 1997) . Camelina seeds contain a high amount of oil (35-43%) which can be used as feedstock for biodiesel production. Camelina oil contains of unsaturated fatty acids (in a high percentage about 90%) naturally, particularly linolenic acid (C18:3; 32.6–38.2 wt.%), linoleic acid (C18:2; 16.9–19.6 wt.%), oleic acid (C18:1; 14.5–19.7 wt.%) and gadoleic acid (C20:1; 12.4–16.2 wt.%) (Ciubota-Rosie et al., 2013; Moser and Vaughn, 2010; Yang et al., 2016). Moreover, Krohn and Fripp, (2012) reported those advantages of false flax biodiesel such as false flax is more environmentally feasible than common feedstocks such as canola and soybean biodiesel depending on it requires lower life cycle energy and emits lower gas emissions which have greenhouse effect when taking land use change into consideration (Krohn and Fripp, 2012).

In this study, effect of compression ratio on performance, noise, vibration and emission characteristics of a variable compression ratio operating with diesel fuel and alternative fuels have been investigated experimentally. Also, effect of compression ratio was investigated numerically and compared with experimental results. False flax, canola and sunflower biodiesels were used as alternative fuels during the experiments.

2. PRELIMINARY WORK

2.1. Biodiesel (Alternative Fuels) Literature Review

It is widely known that transportation is mostly dependent on fossil based petroleum fuels such as diesel fuel, gasoline, compressed natural gas (CNG), and liquefied petroleum gas (LPG). With the decrement of available petroleum resources, the demand for alternative processes to generate fuels (liquid or gaseous) that could potentially help extend the liquid fuels usage and subside the future effects of the poverty of transportation fuels in increasing widely among industry and researchers (Demirbas, 2009a).

Depleting petroleum resources, increment of petroleum prices, harmful effects of exhaust emissions to the environment and critical issues such as global warming requires an intensive international focus in emerging alternative non-petroleum based fuels for internal combustion engines (Muralidharan, 2011).

In the late 1970’s and early 1980’s, taking place of fuel and energy crises was a major and need to be tackled problem in the world. Decreasing petroleum-derived fuels day by day accelerated the interest of researching alternative fuels to use as an energy source. Biodiesel, which is an emerging alternative to diesel fuel, is produced from renewable biological feedstocks such as vegetable oil, animal fats and waste oils. It is biodegradable, non-toxic and emits lower exhausts emissions in some particular cases. Also, the usage of bio based fuels is environmentally friendly. It can be used in diesel (compression ignition engines) with slightly or without any modifications (Ozcanli, 2009). Requirement of alternative fuels and restrictions leaded more researches on this field.

Demirbas (2008) evaluated the methods of biodiesel conversion from vegetable oils and through transesterification reaction. Biodiesel is generally produced by using a chemical reaction of alcohols and fatty acids with a reaction named as transesterification. In the reaction, esters are converted into mono alkyl esters from long chain fatty acids (Demirbas, 2008a).In the means of chemistry, biodiesel is a fatty acid methyl ester. Vegetable oils or waste frying oils can be can be converted to biodiesel (transesterification) by heat treatment of their with a high amount of alcohol and via the presence of a catalyst in the reaction which can be basic or acidic reagent. Generally, a catalyst is used to raise the reaction rate and improved yield. In a transesterification reaction, a higher amount of alcohol (methanol or ethanol) is used to change the reaction equilibrium to the right side and convert more methyl esters as the intended alternative fuel. Many aspects such as the catalyst type (enzyme, acid, or alkaline, , oil molar ratio of alcohol-vegetable, purity rate of reactants (mostly water content and other contaminants), temperature, and free fatty acid value (FFA) have effects on the yield of the reaction of transesterification. Producing biodiesel without catalyst way with supercritical methanol usage developed that lets a simpler process relatively and higher yield of reaction due to the concurrently transesterification of triglycerides and fatty acids methyl esterificationWhen catalytic supercritical methanol transesterification method processed, the conversion yield elevates up to 60–90% for the first one minute (Demirbas, 2008a).

Serin and Akar (2013) investigated the performance and emission characteristics of a diesel engine experimentally when it was fueled with tea seed (Camelina Sinensis) oil methyl ester and its blends with diesel fuel. Also they investigated the fuel properties of tea seed oil biodiesel. The results indicated that fuel properties of tea seed biodiesel was in the range of EN 14214 standards. Study showed that power values showed a decreasing and specific fuel consumption (SFC) values showed an increasing trend since tea seed oil biodiesel has lower calorific value than petroleum based commercial diesel fuel. In contrary, emission characteristics were improved by the using tea seed biodiesel. They reported that CO and CO_2 emissions decreased up to 18.45% and 19.22%, respectively (Serin and Akar, 2013).

Ozcanli (2009) studied Ricinus Communis oil, Pistacia Terebinthus oil and waste chicken oil biodiesels and also experimental studies of performance and exhaust emission characteristics of the engine were performed. The results indicated that in comparison with conventional diesel fuel power and torque values of all biodiesels tended to decrease at high engine speeds. Biodiesel experiments resulted with higher specific fuel consumption since biodiesels have lower calorific value than petroleum based diesel fuel. Oxygen content of biodiesel made CO and CO_2 emissions lower, and as it is expected NO_x emissions increased with usage of biodiesel (Ozcanli, 2009).

Kaplan et al., (2006) presented a study on performance characteristics of sunflower methyl ester as biodiesel. They studied the potential use of sunflower methyl ester as biodiesel and examined the performance characteristics of sunflower biodiesel in a compression engine. The study indicated that performance measures such as torque, power, and specific fuel consumption values were very close to diesel fuel and soot emission improved with sunflower usage (Kaplan et al., 2006).

Yoon et al., (2014) investigated the canola oil and canola oil biodiesel fuel blended fuels effects on combustion and performance characteristics, and emissions decrement in a common rail diesel engine. The study revealed that with the canola oil biodiesel blend ratio increment, indicated mean effective pressure (imep) and the combustion pressure decreased slightly at the low engine speed of 1500 rpm, but these paremeters elevated at the middle engine speed of 2500 rpm. The brake specific fuel consumption (SFC) increased for all engine speeds and, the carbon monoxide (CO) and particulate matter (PM) emissions were significantly decreased. But also, only the nitrogen oxide (NO_x) emissions elevated slightly (Yoon et al., 2014).

Altin et. al., (2001) investigated the effects of the vegetable oil based bio-fuels and methyl esters (raw cottonseed oil, sunflower oil, soybean oil and methyl esters of these oils, refined rapeseed oil, distilled opium poppy oil and refined corn oil) of these oils on a direct injection, diesel engine (single cylinder, four stroke) exhaust emission and performance characteristics. The study revealed that both vegetable oils and esters produced from these oils are potential alternatives for usage in diesel engines as fuel. Vegetable oils still have some problems due to high viscosity, heavy particulate emissions, cold flow properties such as flow, and atomization (Altin et al., 2001).

Koh and Ghazi (2011), reviewed the subject of biodiesel production from Jatropha curcas L. oil. Main disadvantage of biodiesel against petroleum diesel is cost so the oil which are extracted from non-edible seeds and vegetables are getting more attention due to lower
costs. They reported that the raw materials cost generate the 60–75% of the total expense of the biodiesel fuel. According to review, mostly, all off the emissions occured with 100% pure biodiesel (B100) are lower than conventional diesel fuel except for nitrogen oxides NO_x emissions. The NO_x emissions from 100% biodiesel elevate averagely by 10% varying with the combustion characteristics of the test engine, loading variations and the testing procedure (Koh and Ghazi, 2011).

Tuccar (2011) investigated growth characteristics of microalgae to determine the effect of microalgae biodiesel to engine performance parameters and exhaust emissions. The engine performance and exhaust emission measurement experiments showed that the power and torque output of engine fuelled with microalgae biodiesel (MB) decreased by 6% and 5.3% respectively, the emission values were improved with MB usage, namely CO, CO_2 and NO_x emissions decreased by 9.4%, 4.8% and 11.7%, respectively (Tuccar, 2011).

Canakci et. al. (2003) investigated the effect of the biodiesel which is obtained from a high free fatty acid feedstock on performance and emissions characteristics of the engine. The authors prepared two different biodiesels which are from soybean oil and animal fat–based yellow grease with 9% free fatty acids. The refined fuels and 20% blends with No. 2 diesel fuel of these fuels were investigated at steady–state conditions in a four cylinder (turbocharged) compression ignition engine. But, both biodiesel fuels get considerable reductions in carbon monoxide (CO), particulates, and unburned hydrocarbons (UHC), the nitrogen oxides (NO_x) increased by 11% and 13% for the yellow grease methyl ester and soybean oil methyl ester, respectively. The conversion ratio of the biodiesel fuel's energy to usable work was same with that from diesel fuel (Canakci et al., 2003a).

Canakci and Sanli (2008) presented a study on both biodiesel production from different feedstocks and their effects on the fuel properties. Even though biodiesel has some advantages, the greatest obstacle to biodiesel usage is its high cost compared to conventional diesel fuel. Thus, it is necessary to decrease the expense of the biodiesel production to improve its marketability. Compared to high-quality vegetable oils, less expensive feedstocks, such as used frying oils, soapstocks, fats and greases, can be used to lower the cost of biodiesel. But, for these feedstocks, high level of FFA these raw materials restrain the direct application of the transesterification method. The cold flow properties of the biodiesel, particularly produced from fats are not acceptable, because of their high saturation level. However, when branched-chain alcohols are used, comparatively positive properties in the means of the cold flow properties can be obtained. Therefore, the authors suggested to focus on the studies which effort on cold-flow properties improvement of the biodiesels produced from the low-cost feedstocks (Canakci and Sanli, 2008).

Biodiesel is an synthetic altenative fuel to diesel fuel produced from vegetable oils, animal fats or waste cooking oil. Biodiesel may be used as fuel directly, which requires some or no engine modifications, or can be blended with diesel fuel and used in diesel engines some or no modifications (Balat, 2008; Demirbas, 2009a; Demirbas, 2009b; Ilkilic and Yucesu, 2008). Currently, biodiesel provides less than 0.2% of the fuel which is used for transportation (United Nations, 2006). Biodiesel is getting interest recently because of its environmentally friendly characteristics (Lv et al., 2008). However, the cost of biodiesel, is the main problem to commercialization of the fuel. With waste cooking oils used as feedstock, the feasibility of a perpetual transesterification process and high quality glycerol recovery as a biodiesel side product are main options to be study to decrease the cost of biodiesel (Ma and Hanna, 1999; Zhang et al., Balat, 2007a; Utlu, 2007;). Being easily available from common biomass sources, representing a carbon dioxide-cycle in combustion, having significantly environmentally friendly characteristics, having benefits to the environment, local economy and consumers, being biodegradable and sustainable are advantages of biofuels (Puppan, 2002; Demirbas, 2003). Also environmental benefits such as lower greenhouse gas emission and carbon dioxide emissions makes biofuels more attractive for researches. Biofuels creates new employment and economic opportunities in the means of chemical, automotive and agricultural sectors. Biofuel requirement and production is increasing drastically. Figure 2.1 show the biofuel production rates over the years.

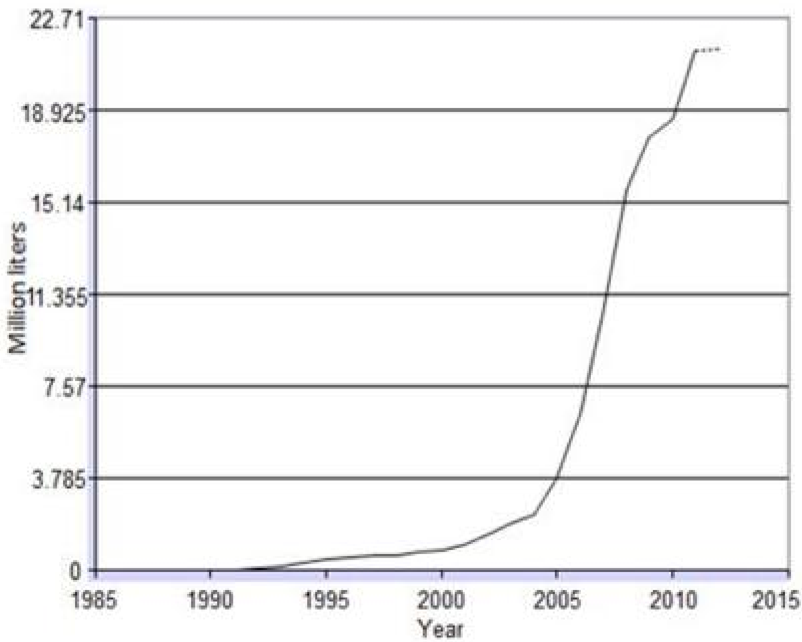


Figure 2.1. World biodiesel production 1991-2012 (Anonymous)

The general European Union (EU) policy objectives regarded most on the subject to the design of energy policy are; European Union economy competitiveness, energy supply security, and protection of environment. All of the renewable energy policies should be evaluated by the benefits they make to these aims. Current European Union policies on alternative engine fuels focus on the usage of biofuels which are renewable (Bozbas, 2008).

Lim and Teong (2010) presented a review which focuses challenges, recent trends and opportunities of biodiesel production in Malaysia. They presented current and previous position of Malaysia in global market of biodiesel, its future potential over the remarkable leading biodiesel condition and basic invasive hitches and the applicability of exploting algae as the future biodiesel raw material in Malaysia in the study. They also mentioned the

economic cost study of biodiesel (Figure 2.2). According to the study, many potential biodiesel raw materials (feedstock) have been investigated such as corn oil in distillers dried grains with soluble, halophyte and soap stock. The authors claimed that in the near future, biodiesel of palm oil should be kept as the essential focus; it will be a long term aim that

multi-feedstock biodiesel as more point will be switched on the quality of products instead of using a raw material alone (Lim and Teong, 2010).

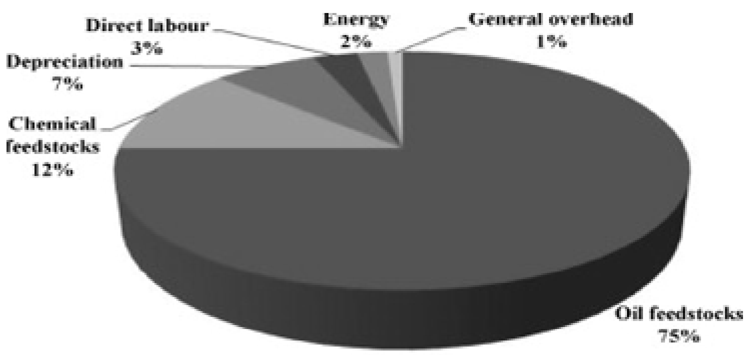


Figure 2.2. General cost breakdown biodiesel. (Lim and Teong, 2010)

Yilmaz and Vigil (2014), investigated the potential use of a blend of diesel, biodiesel, alcohols and vegetable oil in compression ignition engines. They conducted the experiments on a compression ignition engine with diesel-biodiesel-alcohol blends. They blended diesel and biodiesel fuel with alcohols such as ethanol, methanol and butanol. The study indicated that adding alcohols or alcohol–vegetable oil mixtures to biodiesel–diesel blends increases CO and unburned HC emissions while reducing NOx emissions. But, although this may lead to the expectation of lower combustion temperatures, exhaust gas temperatures shows higher values for blends that contain alcohols or alcohol–vegetable oils mixtures. One possible explanation is that unburned fuels with alcohols do not vaporize until the exhaust process due to insufficient time. During the exhaust process, alcohol blended fuels finally react while increasing the exhaust gas temperature, which is relatively lower and may not affect NO_x formation. When comparing alcohols to alcohol–vegetable oil mixtures

as additives, the data shows that adding only alcohols increases CO and HC emissions and decreases NOx emission more than the alcohol–vegetable oil mixture does (Yilmaz and Vigil, 2014).

Yilmaz and Sanchez (2012) represented a paper that investigates the analysis of operating a diesel engine on biodiesel-ethanol and biodiesel-methanol blends. In the study they tested effects of standard diesel, neat biodiesel, biodiesel (85%)-methanol (15%) (B85M15) and biodiesel (85%)- ethanol(15%) (B85E15) fuels. The study demonstrated that biodiesel-alcohol blends cause to increase of brake specific fuel consumption (SFC). Also, biodiesel-ethanol blend results in a lower brake specific fuel consumption than biodiesel-methanol blend, which is possibly due to the higher heat of vaporization of methanol. Exhaust temperature results showed similar characteristics for all of the fuels, and there is no considerable difference through tests. Biodiesel alcohol blends usage caused to increase CO and unburned hydrocarbon emissions in comparison with diesel and pure biodiesel, at below 70% load conditions. With the increment of load, there was no significant difference between the test fuels for carbon monoxide and hydrocarbon emissions (Yilmaz and Sanchez, 2012).

Jianxin et al., (2015), investigated and reported a study that focuses on emission and combustion characteristics of a diesel engine operating with diesel-biodiesel-pentanol fuel blends. They used pentanol to enhance the spraying characteristic and content of oxygen in the blended fuels, which is advantageous for the soot reduction and the fuel–air mixture formation. Study showed that the fuel blends with pentanol addition shows shorter combustion duration and higher maximum heat release rate during the main combustion phase. Higher indicated thermal efficiency and lower indicated specific fuel consumption were also observed for the pentanol blends. Both soot emissions reduced with the pentanol addition and the oxides of nitrogen emissions reduced simultaneously at low middle load during increasing high load in comparison with the diesel fuel. The total hydrocarbon emission reduced, exceptionally for (D70P30), at low engine loads for all the oxygenated blended fuels, and the carbon monoxide emissions also elevated slightly just for 70% diesel, 30% pentanol fuel at the low engine load. The study showed that the addition of pentanol can signifcantly decrease the soot and emissions of carbon monoxide without a considerable impact on oxides of nitrogen and hydrocarbon emissions through the test conditions of a wide load range (Jianxin et al., 2015).

Alcohols as additives to biodiesel–diesel blends were investigated in terms of performance and emission characteristics in diesel engines by many authors. It is reported that the use of alcohol blends up to 20% does not generally need any significant modification (Karabektas and Hosoz, 2009). It has been reported that blends of alcohol–biodiesel with 10% and 15% alcohol concentration elevatehydrocarbon and carbon monoxide emissions whereas addition of 5% alcohol to biodiesel fuels improve these emissions (Yilmaz, 2012). Yilmaz and Vigil (Yilmaz and Vigil, 2014) showed that biodiesel– ethanol and biodiesel–methanol blends reduce NO_x and PM emissions while methanol is more influential than ethanol to improve those emissions. Most of the researchers have used diesel alcohol blends with a small percentage of ethanol, methanol and propanol (Yasin et al., 2013; Yasin et al., 2014).

2.2. Variable Compression Ratio Literature Review

Afterward the 1970 oil crisis, interests of researches on the subject of the internal combustion engines have been explored in the area of alternate fuels, which are produced from renewable feedstocks, available locally, environment friendly compared to fossil fuels (Amarnath and Prabhakaran, 2012). Also, beside fuel researches engine parameters such as compression ratio and injection timing have been studied by the many scientists. These main parameters of engines affect directly performance and emission characteristics of internal combustion engines. Thus, many researchers have investigated the effects of these parameters mostly using variable compression engine (VCR).

Kalam et al., (2011), investigated the emission and performance characteristics of a diesel engine fuelled with waste cooking oil (WCO) 5% palm oil with 95% conventional diesel fuel and 5% coconut oil with 95% conventional diesel fuel. The study revealed that there were decrements in the means of brake power, and decrement in the means of exhaust emissions such as carbon monoxide, smoke, unburned hydrocarbon , (CO), and nitrogen oxides when engine was fuelled with experimental fuels (Kalam et al., 2011).

Mani et al., (2011) investigated the effects of waste plastic oil and waste plastic oil-diesel fuel blends in a compression ignition engine. It was obtained from the study that the 100% waste plastic oil could be used directly to operate the compression ignition engine. Nitrogen oxides emissions were higher 25% and carbon monoxide elevated 5% when the engine was operated with plastic oil compared to diesel fuel. Hydrocarbon emissions were higher about 15%. Smoke emission was elevated compared to diesel fuel about 40% at full load with waste plastic oil usage. Fuelling the engine with waste plastic oil resulted in higher thermal efficiency (BTHE) around 80% at full load conditions and the exhaust gas temperature values were higher for all experiments compared to diesel fuel (Mani et al., 2011).

Yousef et al., (2011) evaluated a study which explores the usage of raw algae oil and its biodiesel in a variable compression ratio engine (Ricardo E6). The authors investigated the effects of engine load, engine speed, compression ratio of the experimental engine, and injection timing of the biodiesel on the engine performance characteristics such as torque and power, and combustion characteristics such as combustion noise (maximum pressure rise rate), maximum pressure experimentally.. Biodiesel usage caused to decrease of engine output torque slightly and also increment in the means of combustion noise was observed by the authors. The authors claimed that engine output can be improved and the combustion noise can be decreased by controlling the engine design parameters e.g. injection timing and compression ratio (Yousef et al., 2011).

Jindal et al. (2010) investigated the e engine design parameters effects with fuel injection pressure and compression ratio on the performance of some important parameters like brake thermal efficiency (BTHE), fuel consumption, and emissions emission characteristics (CO, CO_2, NO_x, smoke opacity) when Jatropha biodiesel used as fuel in the engine. The authors reported that increment injection pressure and compression ratio elevates BTHE and improves brake specific fuel consumption with the results of lower emissions (Jindal et al., 2010).

Mohanraj and Murugu Mohan Kumar (2013) investigated the important operation characteristics of a four stroke variable compression ratio (VCR) engine when the engine was fuelled with esterified tamanu oil. The effects of compression ratio on the performance characteristics like fuel consumption, combustion parameters, and exhaust gas emissions have been studied. The study showed that the brake thermal efficiency of the esterified tamanu oil in VCR engine is slightly higher at higher compression ratios. The brake mean effective pressure (bmep) for the esterified tamanu oil is higher at high compression ratios and lower at low compression ratio. The hydrocarbon emission is higher at low compression ratio and lower for high compression ratio; the increase in compression ratio decreases the hydrocarbon emission for esterified tamanu oil. Nitrogen oxides (NO_x) emissions from the esterified tamanu oil were higher for high compression ratio than that of low compression ratio. The CO emission of the biodiesel is very less at compression ratio of 18 (Mohanraj and Murugu Mohan Kumar, 2013).

Depnath et al. (2012) presented a study that investigates thermodynamic analysis of a variable compression ratio (VCR) diesel engine operating with palm oil biodiesel. They explored the effect of injection timing (IT) and compression ratio (CR) on energy and exergy potential of a palm oil methyl ester (POME) in a diesel engine. Experiments were evaluated under full load conditions in a single cylinder, water cooled, variable compression ratio diesel engine that operates at 1500 rpm constant speed. Study indicated that higher compression ratios usage improves the shaft availability and cooling water availability, but, they reduce the exhaust flow availability. The increment or decrement of injection timing gave similar results with each other. The exergy study also showed that with the increment of compression ratio, the injection increment and decrement improve the shaft availability and exergy efficiency, but also, that increment reduces the destruction of exergy. The entropy generation is also decreased for the similar compression ratio and injection timing modifications (Depnath et al., 2012).

Muralidharan and Vasudevan (2011) carried out an investigation by using waste cooking oil biodiesel and its blends with diesel fuel. The authors exploered the combustion, emission and performance characteristics of a VCR engine. They used a multi fuel, four stroke, single cylinder, variable compression ratio engine when operating with waste cooking oil biodiesel and it’s 80%, 60%, 40% and 20% blends with diesel for experiments. The study showed biodiesel, compression ratio and load are the main parameters that affect the performance characteristics (specific fuel consumption, brake thermal efficiency, brake power, mechanical efficiency and exhaust gas temperature) of an engine. For the alike operating conditions, engine performance decreased with increment in biodiesel ratio in the blend of the test fuel. But, with increasing the compression ratio, the engine performance was comparable with that of conventional diesel (Muralidharan and Vasudevan, 2011).

Amarnath and Prabhakaran (2012) investigated the thermal performance and emissions of a variable compression ratio diesel engine fueled with karanja biodiesel and optimized the parameters based on experimental data. They conducted the experiments on a single cylinder, four stroke direct injection compression ignition engine. The study indicated that at higher compression ratios, the engine gives lower emission and better performance. Brake specific consumption BSFC decreased with increase in load, compression ratio, and injection pressure for all blend fuels. It was observed that unburnt hydrocarbon (UHC) and carbon monoxide (CO) emissions are lower in the case of biodiesel usage, however generation of oxides of nitrogen (NO_x) and smoke intensity was higher with usage of biodiesel (Amarnath and Phabhakaran, 2012).

Paul et al. (2014) presented a paper that studies the combustion, performance, and emission characteristics of a compression igntion engine running with jatropha biodiesel experimentally and numerically (theoretical). They conducted the study experimentally and numerically using DIESEL-RK software. They reported that the use of jatropha biodiesel in a conventional diesel engine reduces torque and brake thermal efficiency of the engine. The decrement of brake thermal efficiency occurred more with increase in the biodiesel ratio in the blends. Cylinder peak pressure elavated and ignition delay period decreased with the increase in biodiesel ratio in the blended fuels (Paul et al., 2014).

Al Dawody and Bhatti (2014), investigated the performance and emission parameters and also combustion characteristics of a diesel engine running with soybean biodiesel-diesel blends experimentally and computationally. The theoretical study was conducted with DIESEL-RK simulation software. They claimed that the usage of biodiesel emitted lower smoke opacity but caused higher brake specific fuel consumption. Biodiesel usage increased NO_x emissions. They compared the experimental computational studies and observed that the result were slightly different with each other (Al Dawody and Bhatti, 2014).

3. MATERIAL AND METHOD

The experimental study was conducted in Petroleum Research and Automotive Engineering Laboratories of the Department of Automotive Engineering at Cukurova University.

3.1. Material

3.1.1. Engine Test Rig

Engine performance experiments were performed on a single cylinder, four stroke, naturally aspirated, water cooled, variable compression multi fuel engine. Technical specifications of the engine were given in Table 3.1. Diesel engine test rig, compression ratio adjustment tools and schematic representation test rig were shown in Figure 3.1 and Figure 3.2. and Figure 3.3, respectively.

Table 3.1. Technical specifications of the engine

Brand	Kirloskar Oil Engines
Model	240
Configuration	Single Cylinder
Type	Four Stroke, Water Cooled
Displacement	661 cc
Bore	87.5 mm
Stroke	110 mm
Maximum/Minimum Operating Speed	2000/1200 rpm
Power	3.5 Kw @ 1500 rpm
CR range	12:1-18:1
Injection Variation	0-25 Deg BTDC
Peak Pressure	77.5 kg/cm^2
Air cleaner	Paper element type
Weight	160 kg
Combustion Principle	Compression Ignition
Lubricating System	Forced Feed System

Figure 3.1. VCR diesel engine test rig

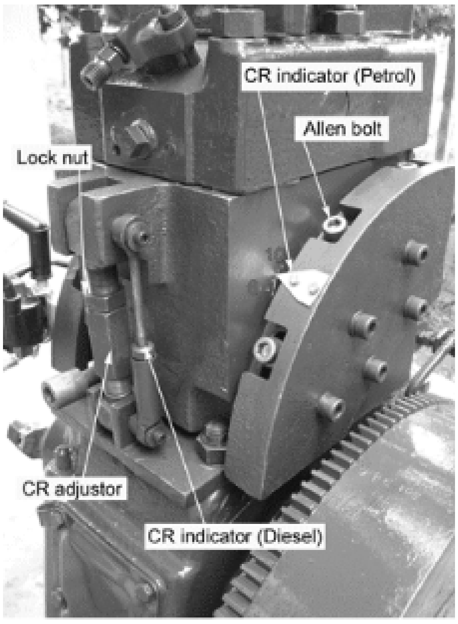


Figure 3.2. Compression ratio adjustment

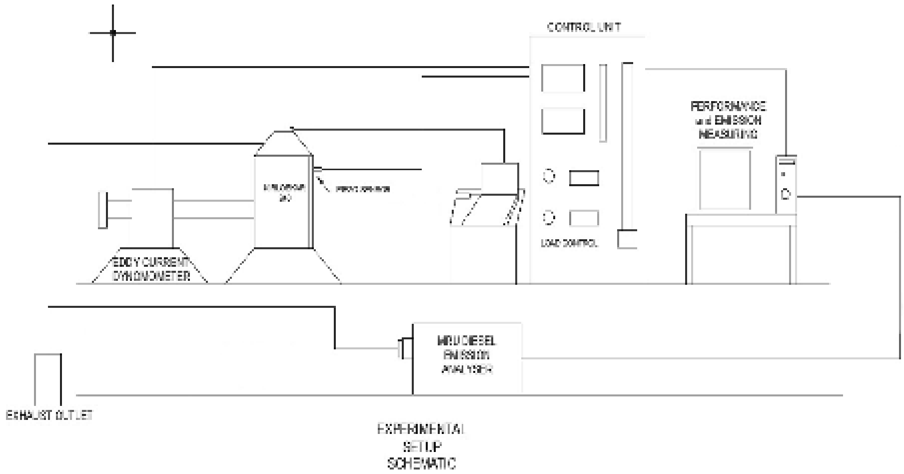


Figure 3.3. Schematic representation of the engine test rig

An eddy current dynamometer and a S-Beam load cell was used for determination of torque and power output. Technical specifications of the dynamometer and load cell are given in Table 3.2 and 3.3.

Table 3.2. Technical specifications of the dynamometer

Model	AG10
Make	Saj Test Plant Pvt. Ltd.
Water inlet	1.6 bar
Torque	11.5 Nm
Hot coil voltage max.	60
Continuous current amps	5
Speed max.	10000 rpm
Load	3.5 kg
Weight	130 kg

Table 3.3. Technical specifications of the load cell

Make	Sensortronics
Model	60001
Type	'S' Beam, Universal
Capacity	0-50 Kg
Non-linearity	<+/-0,025%
Non-repeatability	<+/-0,010%
Operating temperature range	-20 ^{0}C to +70 ^{0}C
Combined error	<+/-0,025%

A piezo sensor was mounted into cylinder for measuring cylinder pressure and combustion analysis. Technical specifications of the piezo sensor used in experiments are given in Table 3.4 and mounting of the sensor is shown in Figure 3.4.

Table 3.4. Technical specifications of the piezo sensor

Sensor name	Dynamic pressure transducer With built in amplifier
Make	PCB Piezotronics, INC.
Model	M111A22
Range, FS (5V output)	5000 psi
Useful range (10V output)	10000 psi
Maximum pressure	15000 psi
Resolution	0.1 psi
Sensitivity	1 mV/psi
Resonant frequency	400 kHz
Rise time	2 μs
Discharge time constant	500 s

Table 3.4. .Continued

Low frequency response (-5%)	0.001 Hz
Linearity (Best straight line)	2 %
Output polarity	Positive
Output impedance	100 ohms
Output bias	8-14 volt
Acceleration sensitivity	0.002 psi/g
Temperature coefficient	0.03 %/0F
Temperature range	-100 to +275 0F
Flash temperature	3000 0F
Vibration / Shock	2000 / 20000 g peak
Ground isolation	No (2)
Excitation (Constant current)	2 to 20 mA
Voltage to current regulator	+18 to 28 VDC
Sensing geometry	Compression
Sensing element	Quartz
Housing material	17.4 SS
Diaphragm	Invar
Sealing	Welded hermetic

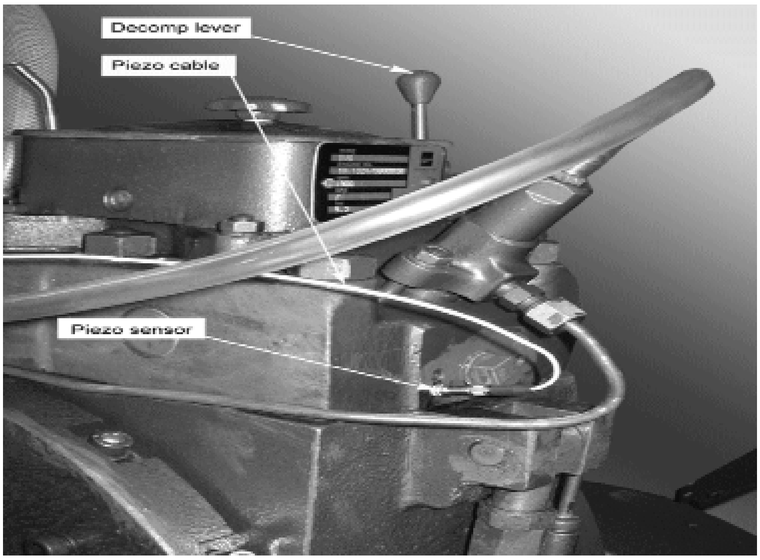


Figure 3.4. Piezo sensor mounting

MRU Air Delta 1600 V mobile exhaust gas analyzer was used to measure exhaust emissions. Emission data was collected with the help of analyzer software. Accuracy of the gas analyzer is ±10 ppm for CO, 1% for CO_2 and ±1 ppm for NO_x. Table 3.3 shows measurement ranges, accuracy and resolution values of emission device.

Table 3.5. Measurement ranges, accuracy and resolution of emission device

Specification	
CO	0-10%
CO2	0-20%
HC	0-20000 ppm
O2	0-22%
NO	0-4000 ppm
NO_2	0-1000 ppm
Lambda	0-9.99
Accuracy	According to OIML-class 1
Ambient Temperature	+5^o - +45 ^{o}C
Exhaust Gas Temperature	Max 650 ^{o}C

Engine performance and emission measurement experiments were executed with different compression ratios (12:1, 14:1 and 16:1) under partial load condition. During the experiments the load was set as 60%. Under this conditions mean brake power of the engine was 2,25 kW and the mean engine torque was 14,55 Nm. Before experimental measurements engine was run 5 minutes to achieve stabile operating conditions. “Enginesoft” software was used for logging experimental data. This software logs for 60 seconds when logging starts and at the end of this period gives the avarege values of experimental datas. Experiments were conducted at 1500 rpm (revolution per minute).

3.1.2. Measurement Devices

The fuel quality measurements were evaluated according to EN 14214, EN 590 and ASTM D 6751. The testing equipment and their measuring methods were briefly explained below.

Density Measurement: The density measurement was done using Kyoto Electronics DA-130 type density-meter (Figure 3.5). This device uses the resonant frequency method to measure the densities. The measurement interval of the device is 0 to 2 g/cm^3 and 0 to 40 ºC. The device has a accuracy of ±0.001 g/cm^3, and a stability of 0.0001 g/cm^3. The device is measuring according to the standards of TS 6311, ASTM D 4052-96.

Figure 3.5. Kyoto Electronics DA-130 portable densimeter

Cetane Number Measurement: Cetane number is a fuel property which shows the fuels's ignition quality. High cetane number means short ignition delay which cause faster combustion in combustion chamber. Zeltex ZX440 device which works under the close infrared spectrometer (NIR) principal was used to measure the cetane number of the test fuels (Figure 3.6). With the help of this method Cetane number measurement was very quick and cheap with only 3% error rate in comparison with the expensive engine tests which requires more time and effort.

Figure 3.6. Zeltex ZX440 cetane measurement device

Flash Point Measurement: The lowest temperature of a combustible mixture can be formed above the liquid fuel is termed as the flash point. It is important for fire safety considerations and depends on both the lean flammability limit of the fuel as well as the vapour pressure of the fuel constituents (Challen and Baranescu, 1999).

Tanaka Automated Pensky-Martens Closed Cup Flash Point Tester with APM-7 model number (Figure 3.7) was used to determine flash point of test fuels. It is conforming the standarts, ISO 2719, ASTM D93, IP 34, ETC. Measuring range varies from ambient temperature to 370 ^{o}C.

Figure 3.7. Tanaka APM-7 flash point tester

Cold Filter Plugging Point Measurement: Cloud point is an important cold flow property of fuels that is especially important in the means operability of diesel fuel under low temperature conditions. The cloud point is the highest temperature at that a wax crystals in liquid first appears during cooling. Running the engine at temperatures lower than the cloud point of a diesel fuel may cause to clog of fuel filters and injectors because of wax crystals. Like description in ASTM D 2500, the cloud point is specified by visually examining for a haze in the originally clear fuel, while the fuel is getting cooled under minutely controlled conditions.

The pour point is another measurement of the cold flow properties of diesel-biodiesel fuels. The lowest temperature of a fuel sample can flow is termed as the pour point. Thus, the pour point gives an index of the lowest temperature of the fuel’s usability for some applications. The pour point also gives some informations for the managing of fuels under cold temperature conditions. ASTM D97 is the standard procedure for the fuels’ pour point measurement.

Cold filter plugging point (CFPP) which is a another cold flow property is the lowest temperature, a standardized amount fuel sample is able to pass through a standard filter system within a designated time while the test sample is cooled under specified conditions. The test provides a forecast for the lowest temperature that a fuel will make problem free flow in fuel systems. That is critical as in cold climate countries; a higher cold filter plugging point means easier the plugging of vehicle fuel delivery systems. This test is essential relevant to the usage of additives that lets deploying the use of winter diesel at temperatures lower than the cloud point. The tests according to EN 590 show that a Cloud point of +1 °C can have a CFPP −10 °C. Some currently used additives allow a CFPP of −20 °C to be based on diesel fuel with a Cloud point of −7 °C. As described in ASTM D6371 CFPP was measured with AFP 102 CFPP tester (Figure 3.8).

Figure 3.8. AFP 102 CFPP tester

Viscosity Measurement: The viscosities of the fuels were measured with Saybolt Universal Viscosimeter (Figure 3.7) produced from Ubbelohde tube with ASTM D88 standards. The measurement results were recorded in seconds. Then using a conversion table the results were converted from SSU (Saybolt Universal Second) to centistokes (cSt) unit. The measurements were conducted at 40 ºC according to the TS EN 14214 standard.

Figure 3.9. Saybolt Universal Viscosimeter

3.1.3. Biodiesel Resources

Vegetable oils and animal fats are becoming a significant option to petroleum diesel fuel depending on the cause that they are renewable and eco-friendly energy sources. In the USA, edible vegetable oils like soybean and canola oil, in Malaysia palm oil, in Europe corn oil and rapeseed oil have been used as raw material for biodiesel production and reported to be a promising diesel altenative. Biodiesel is also produced from animal fats (e.g. beef tallow, pork lard) and used cooking oils (e.g. yellow grease) (NREL, 2009).

In this study, false flax, canola and sunflower oils were used as biodiesel resource. False flax oil was supplied from local oil company at Gaziantep. Canola and sunflower oils were supplied from a local market at Adana, Turkey.

False flax (Camelina Sativa) is a recent crop which has being potential feedstock for biodiesel production and has different uses. With low costs it can be easily grown compared to its counterparts. It belongs to Brassicaceae family and an annual broadleaf oilseed herb which in moderate climates grows well. False flax's meal worthy as animal feed, and its oil contains important nutritional components (alpha linolenic acid and gamma-tocopherol). False flax seeds contain 30-40% oil in its composition which can be converted to biodiesel (Kruczynski, 2012).

After refining the biodiesels, biodiesels and diesel fuel were blended with the ratio of 20%, by volume (20% biodiesel + 80% low sulphur diesel). Test fuels were named as diesel fuel, False Flax B100 (false flax methyl ester), Sunflower B100 (sunflower methyl ester), Canola B100 (canola methyl ester), False Flax B20 (20% False Flax Biodiesel + 80% Diesel), Sunflower B20 (20% Sunflower Biodiesel + 80% Diesel), Canola B20 (20% Canola Biodiesel + 80% Diesel).

Production and tests of biodiesels were carried out in Petroleum Research Laboratories of the Department of Automotive Engineering in Çukurova University. Table 3.6 shows the specifications of diesel and biodiesel fuels used in the analyses. Fuel property tests showed that all test fuels used in experiment were within diesel and biodiesel standards.

Table 3.6. Fuel specifications of test fuels

Properties	Diesel fuel	EN590	False Flax B20	False Flax B100	Sunflwer B20	Sunflower B100	Canola B20	Canola B100	ASTM D 6751	EN 14214
Density, kg/m^3	837	820–845	844	886	844	886	846	883	-	860 - 900
Cetane Number	59,47	Min 51	56,77	52	57,13	53	58,9	54,5	Min 47	Min 51
CFPP, °C	-11	-	-11	-10	-10	-8	-11	-12	-	<4,0 Winter <-
Lower heating value, MJ/kg	45,856	-	41,436	39,048	44,246	39,149	43,413	38,363	-	-
Kinematic viscosity	2,76	2,0–4,5	2,97	4,38	3,1	4,5	3,2	4,7	1,9–6,0	3.5 – 5.0
Flash point °C	79,5	Min 55	91,3	>140	101,5	>140	76,7	120,5	Min 93	Min 120

The density of false flax biodiesel (false flax B100) was found higher than that of diesel fuel. Due to the higher density of false flax biodiesel in accordance with the diesel fuel, blending with false flax biodiesel was caused an increase in the density values. Density measurement results of all blends were within European Biodiesel Standard. The heating value of false flax biodiesel is 14,8% lower than that of diesel fuel. The heating values of false flax biodiesel and diesel fuel were measured as 39,048 and 45,856 MJ/kg, respectively. Cetane number is a measure of the diesel fuel's ignition quality. If the cetane number is too high, before the fuel droplets and intake air are properly mixed in the cylinder early combustion can occur, which causes inproper combustion and emissions of smoke. If the fuel's cetane number is too low, combustion occurs incompletely. Cetane number of false flax biodiesel was measured as 52 which meets the American and European Biodiesel Standards. The temperature at which is the lowest temperature of the standardized volume of fuel can pass through a standardized filter is determined by cold filter plugging point (CFPP). Also, CFPP is a significant property which is relative with pour point. Methyl ester derived from false flax oil has a CFPP of -10 ^{o}C which is significantly low compared with other biodiesel fuels such as palm oil biodiesel, cotton seed oil biodiesel, peanut oil biodiesel. Viscosity, which is resistance to flow a measure of a liquid depending on internal friction of one layer of a fluid moving over another, determine the atomization characteristics of a fuel during injection into the combustion chamber and thus, finally, the engine deposits formation. The general rule is; the higher the viscosity, the greater the tendency of the fuel to cause such problem. Analysis revealed that, false flax biodiesel has higher viscosity value than diesel fuel (4.38 and 2.76 mm^2/s respectively), but; there isn't any problems to adhere standards. Viscosity values of blends showed an increasing trend with the increased false flax biodiesel rates in the blends due to its high viscosity. The lowest temperature at which a fuel sample will vent out sufficient amount of vapor that can flame is termed as the flash point. The flash point measurements give critical information for transportation and storage of the fuel safely. The experiments showed that false flax biodiesel has flash point of over 140 ^{o}C which is acceptable according to European Biodiesel Standards (Yildizhan and Serin, 2015).

3.2. Methods

3.2.1. Transesterification Method

Improvement of fuel properties of oils initiates with reducing their viscosities. In this way, there are two methods available (Figure 3.10).

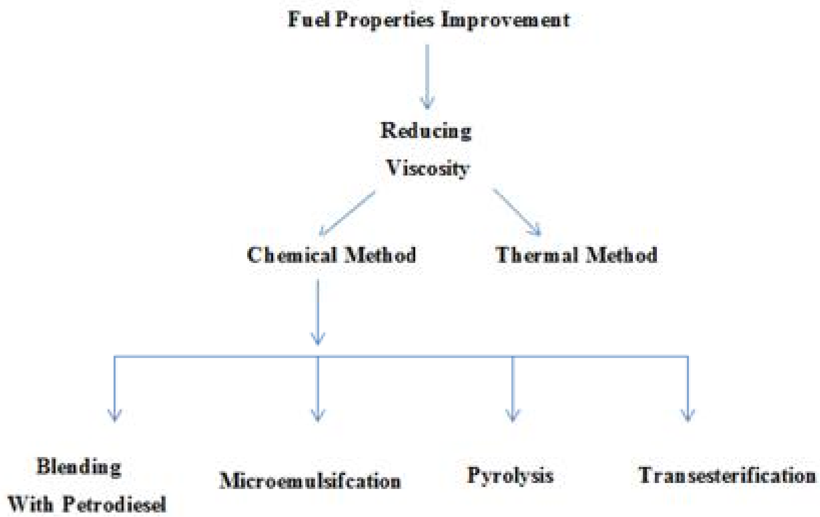


Figure 3.10. Improvement of fuel properties (Alptekin et. al., 2006)

Animal fats or general vegetable oils are saturated and unsaturated monocarboxylic acids esters with the trihydric alcohol glyceride. Those esters are called triglycerides (Leung et. al., 2010). Method of transesterification is reaction of these triglycerides with an alcohol in the presence of a catalyst. At the end of this reaction glycerol and methyl esters are produced (Figure 3.11). Methanol and NaOH (sodium hydroxide) are usually used as alcohol and catalyst, respectively.

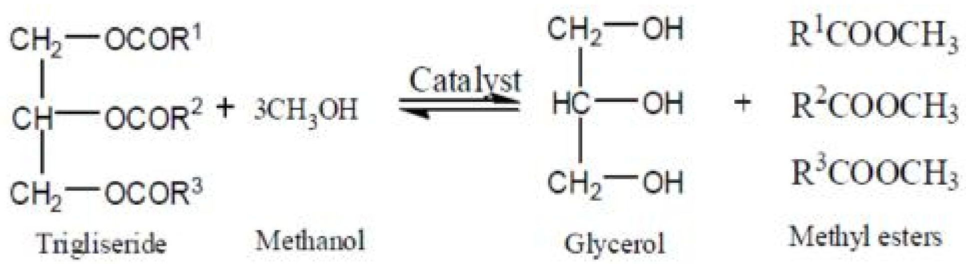


Figure 3.11. Chemical structure of transesterification reaction

Molar ratio of alcohol to oil should be 3:1 for a stoichiometric reaction. At the end of reaction 3 moles methyl ester (biodiesel) and 1 mol glycerol are produced. In order to increase production conversion, molar ratio of alcohol to oil can be increased. For example, production conversion is % 89,7 when molar alcohol to oil ratio is 3:1 and % 98,9 when ratio is 6:1 (Alptekin et al., 2006; Tosun, 2013).

The experimental study was conducted in Petroleum Research and Automotive Engineering Laboratories of the Department of Automotive Engineering at Cukurova University, Adana, Turkey.

To be able to provide best condition for production, transesterification reactions were carried out in a spherical glass reactor equipped with reflux condenser, stirrer and thermometer (Figure 3.12). In the reactions, molar ratio of alcohol to oil was 6:1. The reactions were performed with, methanol 20 wt %, sodium hydroxide 0,5 wt %. Methanol and sodium hydroxide were reacted in order to obtain sodium methoxide. Then, sodium methoxide and oil samples were blended in the reactor. The mixtures were heated up to 65 ^oC and kept at this temperature for 90 minutes by stirring. After the reaction period, the crude methyl esters were waited at separating funnel for 8 hours. And then, crude glycerin was separated from methyl ester. Finally, the crude methyl esters were washed with warm water until the washed water became clear and then, it dried at 110 ^oC for 1 hour. Finally washed and dried methyl esters were passed through a filter one hour. In order to neglect the possibility of impurities, the methyl ester drained from paper filter. Biodiesel production flow diagram is shown in Figure 3.13. Figure 3.14 and Figure 3.15 show the batching and drying processes of biodiesel production.

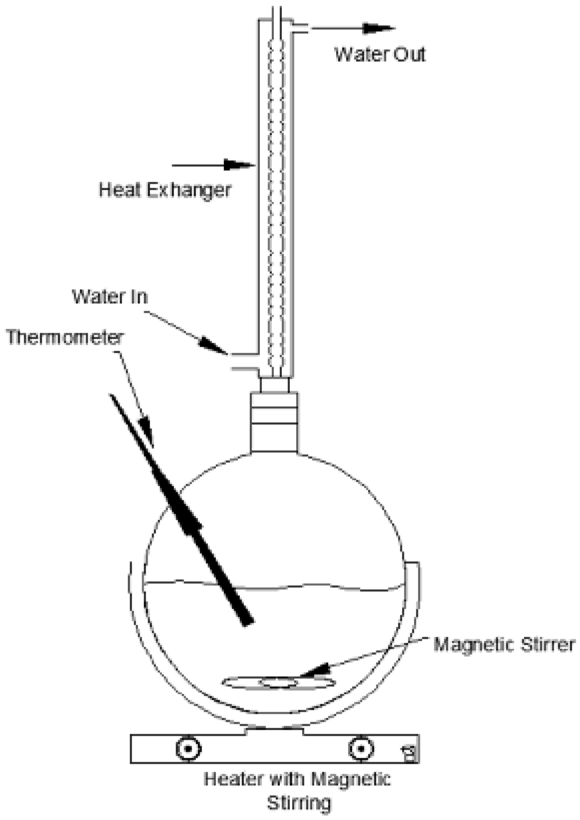


Figure 3.12. Small scale reactor

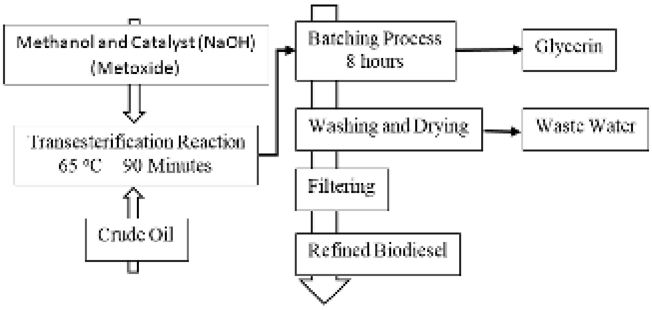


Figure 3.13. Biodiesel production flow diagram

Figure 3.14. Batching process

Figure 3.15. Drying process

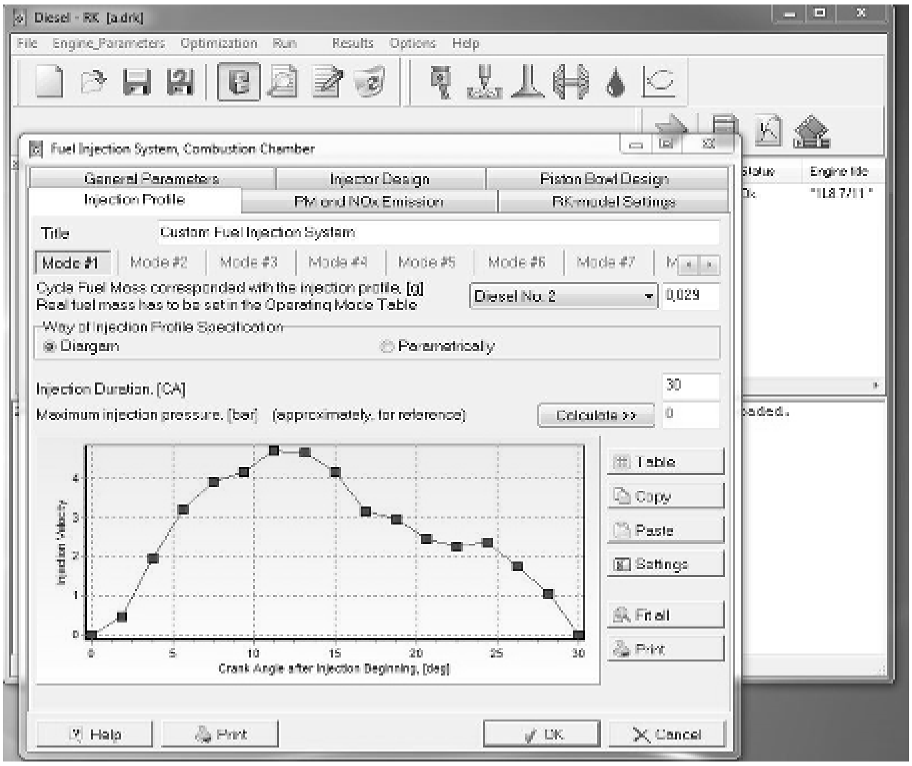
3.2.2. Diesel-RK Simulating Software

Diesel-RK is engine simulation software of full cycle thermodynamic. It is designed for optimizing and simulating four and two stroke internal combustion engines working processes via boosting options of all types. This software can be utilized for modeling studies of the types of engines as follows:

- Diesel engines, including premixed charge compression ignition (PCCI) and engines running with bio-fuels.
- Gasoline (spark ignition) engines including pre-chamber systems, and also engines operating with different gases: Wood gas, Methane, Biogas, Syngas, Propane-Buthane, etc.

To evaluate an optimization calculation, the software is equipped with a built-in procedure of multi-parametric and multi-dimensional optimization which includes 14 methods of nonlinear optimization search. It also lets to evaluate 1D and 2D parametrical search investigations. Tools of optimization let researchers to considerable increase the efficiency of computational research giving useful ways to enhance the designing process of the engine. For simultaneous optimization of few engine parameters: oxides of nitrogen, soot and specific fuel consumption the aim function with engine parameters list may be calculated with User Defined Procedure being performed as and connected to the existing Diesel-RK kernel.It is possible to run a Pareto-optimization if Diesel-RK will be operated under the control of external optimizer (Diesel-RK website, 2016).

The Diesel-RK software combustion module supports the library of various fuels types including various mixtures diesel oil of with biofuels. Biofuel blends physical properties of are used in in modeling the evaporation, the spray evolution simulations and and processes of combustion. Figure 3.16 (a,b,c,d) shows the print screens of Diesel-RK simulation software operating.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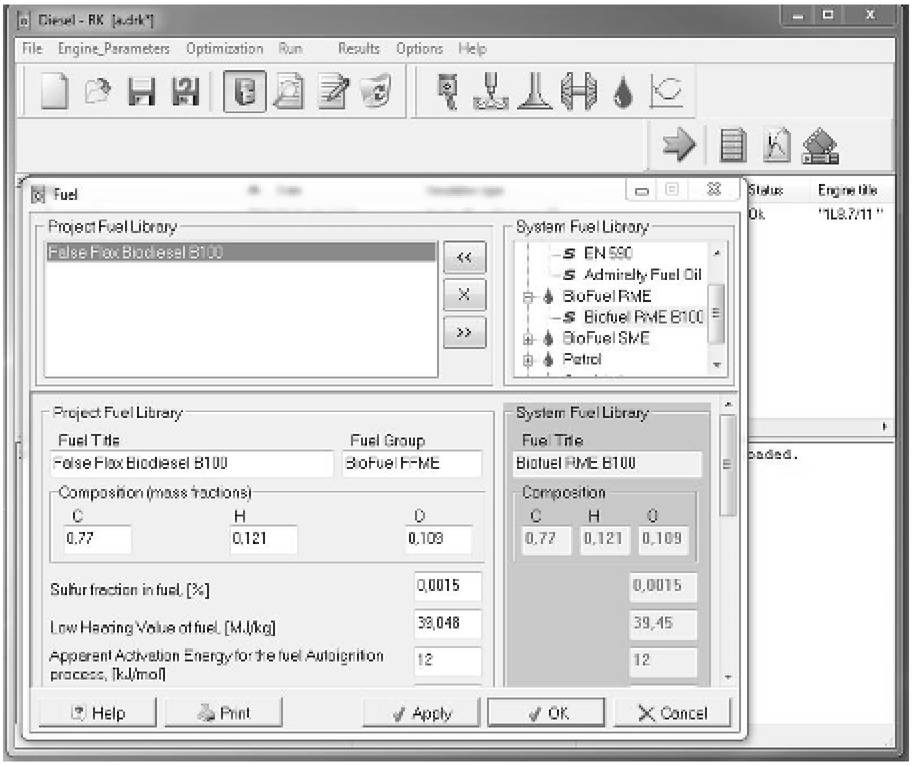
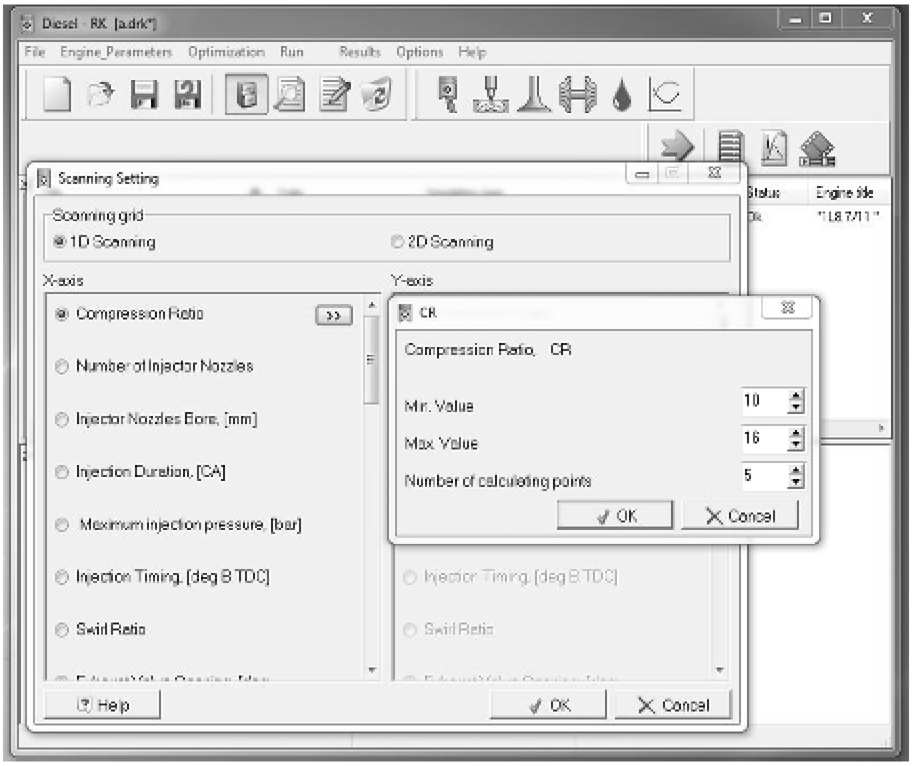
File Engine_Parameters Optimization Run Results Options Help
Fuel Injection System, Combustion Chamber
General Parameters
Injector Design
Piston Bowl Design
Injection Profile
PM and NOx Emission
RK-model Settings
Title
Custom Fuel Injection System
Mode #1
Mode #2
Mode #3
Mode #4
Mode #5
Mode #6
Mode #7
Cycle Fuel Mass corresponded with the injection profile, [g]
Real fuel mass has to be set in the Operating Mode Table
Diesel No. 2
0,029
Way of Injection Profile Specification
Diargam
Parametrically
Injection Duration, [CA]
30
Maximum injection pressure, [bar] (approximately, for reference)
Calculate >>
0
Table
Copy
Paste
Settings
Fit all
Print
Injection Velocity
Crank Angle after Injection Beginning, [deg]
Help
Print
OK
Cancel
Status
Engine title

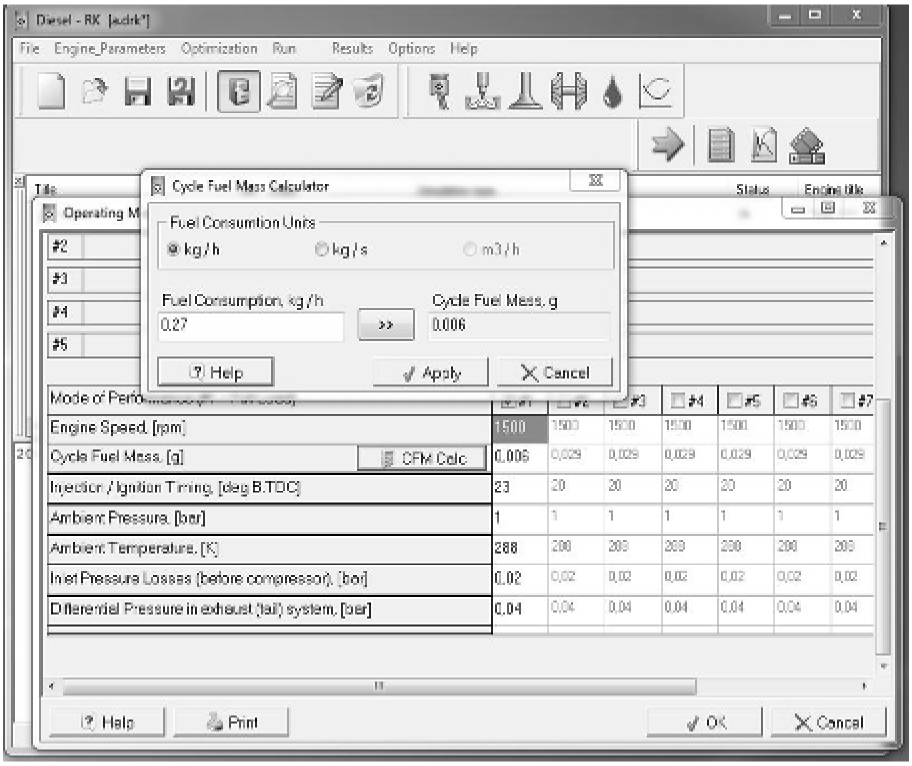
(a)


Diesel - RK [a.drk*]
File Engine_Parameters Optimization Run Results Options Help
Fuel
Status Engine title
Ok "1L9.7/11"
Project Fuel Library
False Flax Biodiesel B100
System Fuel Library
EN 590
Admiralty Fuel Oil
BioFuel RME
Biofuel RME B100
BioFuel SME
Petrol
Project Fuel Library
Fuel Title
False Flax Biodiesel B100
Fuel Group
BioFuel FFME
Composition (mass fractions)
C H O
0,77 0,121 0,109
Sulfur fraction in fuel, [%] 0,0015
Low Heating Value of fuel, [MJ/kg] 39,048
Apparent Activation Energy for the fuel Autoignition process, [kJ/mol] 12
System Fuel Library
Fuel Title
Biofuel RME B100
Composition
C H O
0,77 0,121 0,109
0,0015
39,45
12
Help
Print
Apply
OK
Cancel

(b)


Diesel - RK [a.drk*]
File Engine_Parameters Optimization Run Results Options Help
Scanning Setting
Scanning grid
1D Scanning
2D Scanning
X-axis
Y-axis
Compression Ratio
Number of Injector Nozzles
Injector Nozzles Bore, [mm]
Injection Duration, [CA]
Maximum injection pressure, [bar]
Injection Timing, [deg B TDC]
Swirl Ratio
Help
OK
Cancel
CR
Compression Ratio, CR
Min. Value
10
Max Value
16
Number of calculating points
5
OK
Cancel
Status
Engine title

(c)



(d)

Figure 3.16. Diesel-RK simulation software operating screenshots (a,b,c,d)

3.2.3. Diesel Engines and Variable Compression Ratio (VCR) Test Engine

The most significant characteristic of the diesel (compression ignition) engine is its greater efficiency of fuel, which can exceed 40% in vehicular applications and even 50% in large, two-stroke units of electrical generation or marine propulsion. Eventually, vehicles operating with compression ignition engines acquire relatively much lower specific fuel consumption and lower emissions of carbon dioxide than their rated counterparts (gasoline-spark ignition engines) throughout the all operating range, which provides significant economy over the vehicle’s lifetime. Furthermore, compression ignition engines are expressed precisely low sensitive to air–fuel ratio variations, no throttling, relatively higher torque and higher tolerance in the means of peak cylinder pressures and temperatures that complies with the applications of various schemes of supercharging. The experimental setup consists of four stroke, single cylinder, multi-fuel, research engine equipped with an eddy current type dynamometer for loading. The mode of operation of the experimental engine can be changed from petrol to diesel or from diesel to petrol with some necessary equipment changes. For the both diesel and petrol modes, the compression ratio of the cylinder can be varied without ceasing the engine and without changing the geometry of combustion chamber by tilting cylinder block arrangement. The standard available engines (with fixed compression ratio) can be modified to variable compression ratio by modifying with additional variable combustion space. There are some different arrangements which can provide this process (Kirloskar Oil Engines Manual, 2010). Tilting cylinder block method is one of the arrangements where the compression ratio can be changed without change is combustion geometry . With this method the compression ratio can be changed within designed range without ceasing the engine (Figure 3.17).

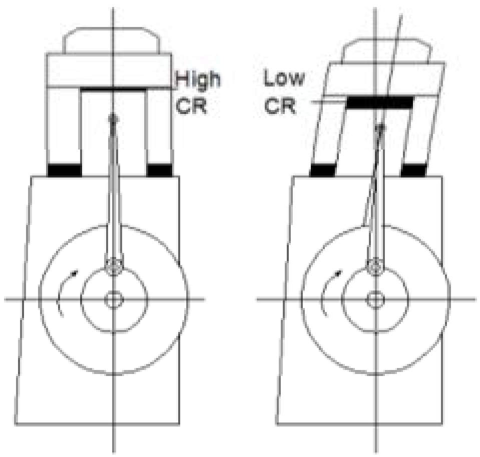


Figure 3.17. Tilting cylinder block arrangement

Setup is equipped with required instruments for measurement of combustion pressure, measurements of crank-angle, and pressure of diesel line. For pressure crank-angle diagram, signals from the test rig are interfaced with computer. Instruments are equipped with measurement of fuel flow, interface airflow, measurements of temperatures and load. The setup includes a stand-alone panel box consisting of two fuel tanks for duel fuel test, air box, , , transmitters for air, fuel measuring unit, manometer and measurements of fuel flow, indicators of process and hardware interface. Rotameters are included for water cooling and also calorimeter for measurement of water flow. For engine electric initiate arrangement a battery pack, starter and battery charging unit is provided. The setup lets to study of cvariable compression ratio engine performance for indicated power, brake power, frictional power, brake mean effective pressure, indicated mean effective pressure, indicated thermal efficiency, brake thermal efficiency, volumetric efficiency, mechanical efficiency, specific fuel consumption, air/fuel ratio, heat balance and combustion analysis. Labview based Engine Performance Analysis software package "Enginesoft" is included for on line performance analysis (Kirloskar Oil Engines Manual, 2010). When analyzing an engine some terms should be defined clearly:

- Engine cylinder diameter (bore) (D): Working cylinder's nominal inner diameter of the.
- Piston area (A): The area of an engine cylinder (bore). $A = \pi / 4 \times D^2$
- Engine stroke length (L): The nominal distance between bottom and top dead centers which a piston moves between.
- Dead center: The position of the the moving parts and working piston, that are mechanically linked to it at the moment the time that the piston direction motion is reversed to opposite direction (at either end point of the stroke).
- Bottom dead center (BDC): Dead center when the piston is at a position at a nearest to the crankshaft. Sometimes it is also called outer dead center (ODC).

- Top dead center (TDC): Dead center when the position is farthest from the crankshaft. Sometimes it is also called inner dead center (IDC).
- Swept volume (V_s): The nominal volume which is generated by the piston working when travelling from bottom dead center to top dead center, calculated from the product of piston area and stroke. The capacity described by engine manufacturers in cc is the swept volume of the engine. $V_s = A \times L = \pi / 4 \times D^2$
- Clearance volume (V_c): The space nominal volume on the combustion side (where combustion occurs) of the piston at top dead center.
- Cylinder volume: The sum of swept volume and clearance volume. $V=V_s+V_c$
- Compression ratio (CR): The numerical ratio of the smallest volume to highest volume, calculated by cylinder volume divided by the numerical value of clearance volume. $CR = V / V_c$

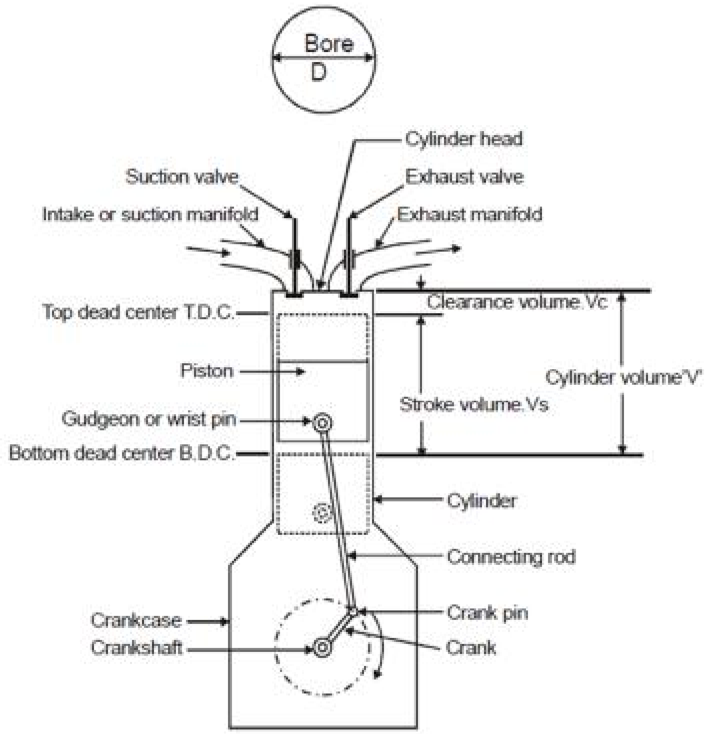


Figure 3.18. Important positions and volumes in reciprocating engine (Kirloskar Oil Engines Manual, 2010)

In four-stroke cycle engine, a full cycle of operation is completed in four strokes of the piston or two revolutions of the crankshaft. Each stroke of crankshaft consists of 180^o rotation and thus a full cycle of crankshaft rotation consists of 720^o (Kirloskar Oil Engines Manual, 2010). The series of operation of an ideal four-stroke engine are as follows:

- Suction or Induction stroke: The inlet valve is opened, and the piston goes downward the cylinder, sucks in a charge of air. In spark ignition engines, the air is generally pre-mixed with the fuel.
- Compression stroke: All valves are closed, and the piston goes upward the cylinder. Before the piston arrives the top dead center (TDC), ignition

initiates. In compression ignition engines, the fuel is injected at the end of the compression stroke by fuel injectors.

- Working or Power or Expansion stroke: Combustion spreads throughout the fuel-air mixture, increasing the temperature and pressure, and pushing down the piston. The exhaust valve is opened at the end of the expansion stroke, and the ‘blow-down’ term is given to irreversible expansion of the exhaust gases.
- Exhaust stroke: The exhaust valve is kept opened, and with the upward motion of piston in the cylinder, the residual gases are pushed out. At the end of the exhaust stroke, exhaust valve is closed but, some exhaust gas residuals will remain inside cylinder; these residual gases will dilute the upcoming fuel-air charge.

Performance parameters of internal combustion engines are as follows :

Indicated thermal efficiency (η_t): Indicated thermal efficiency is the ratio of energy in the indicated power to the fuel energy.

$$(\eta_t) = \text{Indicated Power} \ / \ \text{Fuel Energy} \tag{3.1.}$$

$$\eta_t(\%) = \frac{IndicatedPower(kW)\times 3600}{FuelFlow\left(\frac{Kg}{Hr}\right)\times \text{CalorificValue}\left(\frac{\text{Kj}}{\text{Kg}}\right)} \times 100 \tag{3.2.}$$

- Brake thermal efficiency (η_{th}): A measure of overall efficiency of the engine is given by the brake thermal efficiency. Brake thermal efficiency is the ratio of energy in the brake power to the fuel energy. Figure A shows the pressure (P) – volume (V) and temperature (T) – entropy (S) diagrams of idealized diesel cycle.

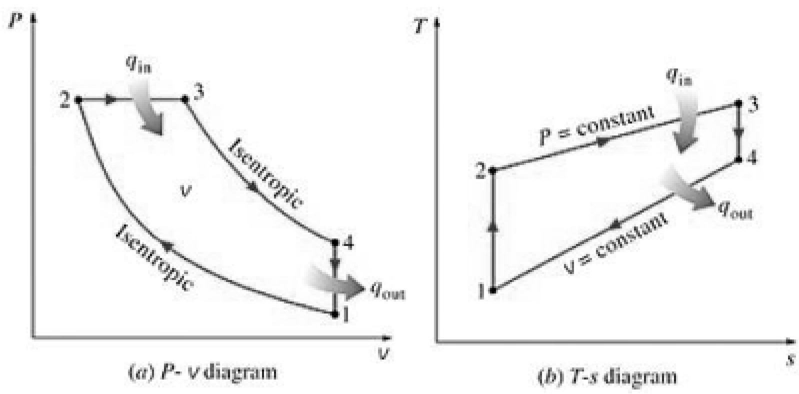


Figure 3.19. P-V and T-S diagrams of idealized diesel cycle (Anonymous)

Thermodynamically;

$W_{cycle} = \oint PdV = \oint Tds$ (3.3.)

$Q_{2-3} = \int_{T_2}^{T_3} c_p dT$ $Q_{4-1} = -\int_{T_4}^{T_1} c_v dT$

$Q_{2-3} = c_p(T_3-T_2)$ $Q_{4-1} = -c_v(T_1-T_4) = c_v(T_4-T_1)$

$\eta_{th} = \frac{Q_{2-3}-Q_{4-1}}{Q_{2-3}}$ $\eta_{th} = 1 - \frac{Q_{4-1}}{Q_{2-3}}$ $\gamma = \frac{c_p}{c_v}$ (3.4.)

$\eta_{th} = 1 - \frac{c_v(T_4-T_1)}{c_p(T_3-T_2)}$ $\eta_{th} = 1 - \frac{(T_4-T_1)}{\gamma(T_3-T_2)}$

$\alpha = \frac{V_3}{V_2}$

Since 1-2 adiabatic

$T_2 = T_1 r^{\gamma-1}$ ((3.5.)

Since 2-3 constant pressure

$P_2V_2 = mRT_2$ $P_3V_3 = mRT_3$ $T_3 = T_2 \frac{V_3}{V_2}$ (3.6.)

$T_3 = T_2\,\alpha$ $T_3 = T_1\,\alpha r^{\gamma-1}$

$P_4V_4^{\gamma} = P_3V_3^{\gamma}$ $P_4V_4V_4^{\gamma-1} = P_3V_3V_3^{\gamma-1}$

$P_4V_4 = mRT_4$ $P_3V_3 = mRT_3$ $\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1}$

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{V_3}{V_2}\right)^{\gamma-1}\left(\frac{V_2}{V_4}\right)^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}\left(\frac{\alpha^{\gamma}-1}{\gamma(\alpha-1)}\right) \quad (3.7.)$$

(η_{th}) = Brake Power/Fuel Energy (3.8.)

$$\eta_{th}(\%) = \frac{BrakePower(kW)\times 3600}{FuelFlow\left(\frac{Kg}{Hr}\right)\times \text{CalorificValue}\left(\frac{\text{Kj}}{\text{Kg}}\right)} \times 100 \quad (3.9.)$$

Where;

η_{th} is thermal efficiency,

α is the cut-off ratio (ratio between the end and start volume for the combustion phase),

c_p is specific heat at constant pressure,

c_v is specific heat at constant volume,

γ is ratio of specific heats (c_p/c_v),

r is the compression ratio.

Theoretical equation shows that thermal efficiency of the diesel cycle depends on three parameter which are; compression ratio (r), ratio of specific heats (γ) and cut-off ratio of the cycle (α).

- Mechanical efficiency (η_m): Mechanical efficiency is the ratio of brake horse power (delivered power) to the indicated horsepower (power provided to the piston).

  (η_m) = Brake Power / Indicated Power

  Frictional Power = Indicated Power – Brake Power (3.10.)

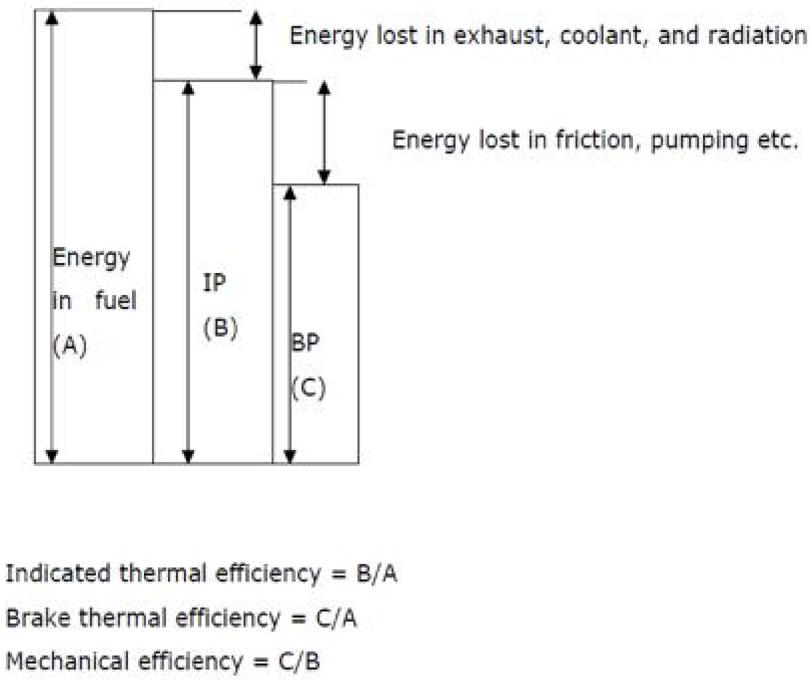


Figure 3.20. The difference between reversible work and actual useful work (Kirloskar Oil Engines Manual, 2010)

- Volumetric efficiency (η_v): The engine output is limited by the maximum amount of air that can be taken in during the suction stroke, because only a certain amount of fuel can be burned effectively with a given quantity of air. Volumetric efficiency is an indication of the 'breathing' ability of the engine and is defined as the ratio of the air actually induced at ambient conditions to the swept volume of the engine. In practice, the engine does not charge a complete cylinder full of air on each stroke, and it is convenient to define volumetric efficiency as:

$$(\eta_v) = \text{Actual air inducted / Theoretical air} \quad (3.11.)$$

$$\eta_v(\%) = \frac{\text{AirFlow(Kg/Hr)}}{\pi\ /\ 4 \times \text{D2L(m3)} \times \text{N(rpm)}/\text{n} \times \text{noc} \times \text{AirDen}\left(\frac{\text{Kg}}{\text{m3}}\right) \times 60} \times 100 \qquad (3.12.)$$

Where n= 1 for 2 stroke engine and n= 2 for 4 stroke engine.

- Specific fuel consumption (SFC): Brake specific fuel consumption and indicated specific fuel consumption, abbreviated BSFC and ISFC, are the fuel consumptions on the basis of Brake power and Indicated power respectively.
- Fuel-air (F/A) or air-fuel (A/F) ratio: The relative proportions of the fuel and air in the engine are very important from view of combustion and efficiency of the engine. This is expressed either as the ratio of the mass of the fuel to that of the air or vice versa.
- Calorific value or Heating value or Heat of combustion: It is the energy released per unit amount of the fuel, when the combustible is burned and the products of combustion are cooled back to the initial temperature of combustible mixture. The heating value so obtained is called the higher or gross calorific value of the fuel. The lower or net calorific value is the heat released when water in the products of combustion is not condensed and remains in the vapor form.
- Power and Mechanical efficiency: Power is defined as rate of doing work and equal to the product of force and linear velocity or the product of torque and angular velocity. Thus, the measurement of power involves the measurement of force (or torque) as well as speed. The power developed by an engine at the output shaft is called brake power and is given by;

Power = NT/60,000 in kW

Where T= torque in Nm = WR

W = 9.81 * Net mass applied in kg. R= Radius in m

N is speed in RPM

- Mean effective pressure and torque: Mean effective pressure is defined as a hypothetical pressure, which is thought to be acting on the piston throughout the power stroke.

  Power in kW = (Pm LAN/n 100)/60 in bar

  where Pm = mean effective pressure

  L = length of the stroke in m

  A = area of the piston in m^2

  N = Rotational speed of engine RPM

  n= number of revolutions required to complete one engine cycle

  n= 1 (for two stroke engine)

  n= 2 (for four stroke engine)

  Thus we can see that for a given engine the power output can be measured in terms of mean effective pressure. If the mean effective pressure is based on brake power it is called brake mean effective pressure (BMEP) and if based on indicated power it is called indicated mean effective pressure (IMEP).

$$\text{BMEP(bar)} = \frac{BrakePower(kW)\times 60}{L\times \mathrm{A}\times(\frac{\mathrm{N}}{\mathrm{n}})\times \mathrm{noc}\times 100} \quad (3.13.)$$

$$\text{IMEP(bar)} = \frac{Indicated<Power(kW)\times 60}{L\times \mathrm{A}\times(\frac{\mathrm{N}}{\mathrm{n}})\times \mathrm{noc}\times 100} \quad (3.14.)$$

3.2.4. Combustion in Diesel Engines

Combustion of diesel engines is a complex phenomenon which includes the time from starting the injection of fuel into combustion chamber to the starting of exhaust stroke which combustion products are pushed out (Heywood, 1988).

Generally, fuel-air mixture inside the cylinders of diesel engine is not completely homogenous. Combustion occurs with the injection of fuel in to the combustion chamber which has high temperature and pressure. Combustion reactions occur when the fuel is injected and starts to evaporate. At the first stages of combustion, cylinder pressure does not increase explicitly since reaction rate is low. After the ignition delay time period, the flame in the combustion chamber can be observed and the increase of cylinder pressure becomes clear in p-V diagram (Heywood, 1988). In the case of diesel engines, after the ignition delay time period, local conditions of combustion chamber such as pressure, temperature and also mass and heat transfers inside the combustion chamber determine the characteristic of combustion. Combustion of diesel engines can be divided into 4 categories,

- Ignition delay period
- Premixed combustion phase
- Mixing-controlled combustion phase
- Late combustion phase

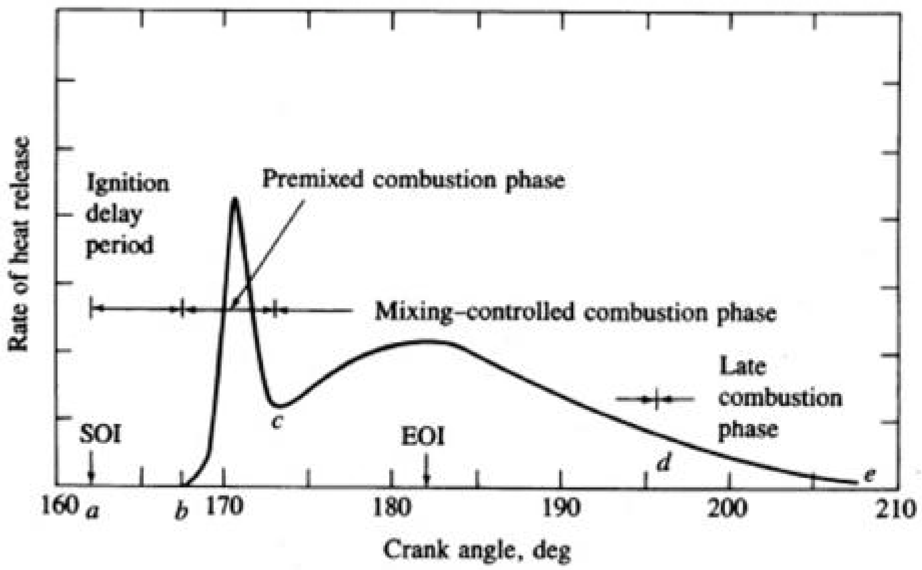


Figure 3.21. Combustion stages of a diesel (CI) engine (Heywood, 1988)

Atomization of fuel droplets, evaporation of fuel and chemical reactions (oxidation) starts with the injection of fuel. But, there is particular time between the injection of fuel and emerging of flame. The time from injection point to emerging the flame and sudden increase of pressure in p-V diagram is called as ignition delay time (Heywood, 1988).

Ignition delay time is a very important factor that affects the combustion characteristics. Ignition delay time is affected by many parameters;

- Cylinder temperature
- Cylinder pressure
- Engine speed
- Intake air temperature and pressure
- Load condition of the engine
- Oxygen concentration
- Compression ratio
- Cooling characteristics of the engine
- Injection characteristics
- Fuel characteristics

4. RESULTS AND DISCUSSIONS

4.1. Error Analysis

Since engine operating is a very complex mechanism and there are too much parameter which affect the engine performance, average engine speeds were slightly different from 1500 rpm. Table 4.1 and 4.2 shows the error analysis of experimental datas according to engine load and engine speed, respectively. Analysis shows that the maximum error of engine speed was 1,76% for engine speed variation according to 1500 rpm. Table 4.1 and 4.2 show the error analysis values (standard deviation and standard error) for engine speed engine torque and engine speed values, respectively.

Table 4.1. Error analysis of experimental torque values

Experiments			Average (Mean)		Standard Deviation (σ)	Standard Error (σ_m)
			Each Fuel	All Test Fuels		
Fuel	CR	Engine Brake Torque (Nm)	$\bar{x} = \frac{1}{n}\sum_{1}^{n} x_i$		$\sigma = \sqrt{\frac{\sum_{1}^{n}(x_i - \bar{x})^2}{n-1}}$	$\sigma_m = \frac{\sigma}{\sqrt{n}}$
Diesel	12:1	14,33	14,67	14,5509	0,05389	**± 0,05389**
	14:1	14,95				
	16:1	14,73				
Sunflower B20	12:1	14,47	14,5			
	14:1	14,75				
	16:1	14,28				
Sunflower B100	12:1	14,65	14,5833			
	14:1	14,32				
	16:1	14,78				
Canola B20	12:1	14,84	14,54			
	14:1	14,4				
	16:1	14,38				
Canola B100	12:1	14,97	14,73			
	14:1	14,78				
	16:1	14,44				
False Flax B20	12:1	14,51	14,5366			
	14:1	14,5				
	16:1	14,6				
False Flax B100	12:1	14,54	14,2966			
	14:1	13,91				
	16:1	14,44				

$$x = \bar{x} + \sigma_m = \bar{x} \pm \frac{\sigma}{\sqrt{n}}$$

$$x = 14,5509 \pm 0,05389$$

Table 4.2. Error analysis of experimental engine speed values

Experiments			Average (Mean)		Standard Deviation (σ)	Standard Error (σ_m)
			Each Fuel	All Test Fuels		
Fuel	CR	Engine Speed (rpm)	$\bar{x} = \frac{1}{n}\sum_{1}^{n} x_i$		$\sigma = \sqrt{\frac{\sum_1^n (x_i - \bar{x})^2}{n-1}}$	$\sigma_m = \frac{\sigma}{\sqrt{n}}$
Diesel	12:1	1481	1470	1476,9523	15,36067	**± 3,3519**
	14:1	1475				
	16:1	1454				
Sunflower B20	12:1	1472	1483			
	14:1	1482				
	16:1	1495				
Sunflower B100	12:1	1505	1469			
	14:1	1450				
	16:1	1454				
Canola B20	12:1	1477	1486			
	14:1	1498				
	16:1	1484				
Canola B100	12:1	1475	1483			
	14:1	1504				
	16:1	1470				
False Flax B20	12:1	1477	1467,66			
	14:1	1464				
	16:1	1462				
False Flax B100	12:1	1493	1479			
	14:1	1475				
	16:1	1469				

$$x = \bar{x} + \sigma_m = \bar{x} \pm \frac{\sigma}{\sqrt{n}}$$

$$x = 1476{,}9523 \pm 3{,}3519$$

4.2. Combustion Characteristics

The combustion of diesel engine is extremely complex which depends on many parameters such as fuel, engine design, ignition timing, compression ratio, injection profile and etc. (Gnanamoorthi and Devaradjane, 2015). The combustion phenomena depends on many engine parameters such as engine design, fuel, compression ratio, injection timing, engine temperature, intake air pressure, engine load, and etc. The combustion of diesel engine is generally occurs as partially pre-mixed.. Figures 4.1-4.7 shows the cylinder pressure characteristics of the test fuels with CRs 12:1, 14:1 and 16:1. It can be seen from the graphs that CR increment increased peak cylinder pressure for all test fuels as it is expected. The increase of CR provides better mixing of fuel-air and leads to higher combustion temperature. Higher CR provides the reducing ignition delay and thus the combustion occur near the TDC (top dead center) (Li et al., 2015). The graphs show that the combustion of higher CR experiments occurs closer to TDC. Higher CR provides the reducing ignition delay and thus the combustion occur near the TDC (top dead center) (Gnanamoorthi and Devaradjane, 2015). The experimental results revealed that increasing CR from 12:1 to 16:1 increased maximum cylinder pressure 14,504% for diesel fuel. Due to better mixing of fuel droplets, higher compression pressure and temperature; better combustion of fuel was obtained and thus higher maximum cylinder pressure was measured.

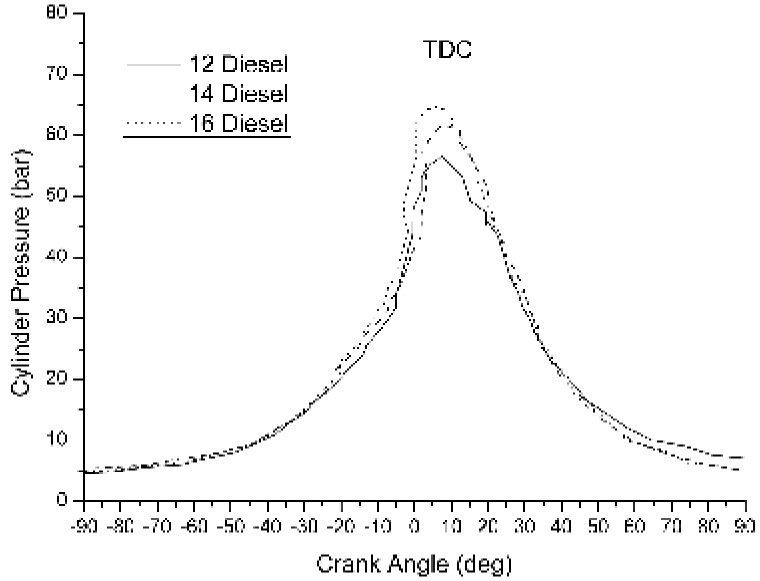


Figure 4.1. Cylinder pressure graph of Diesel fuel

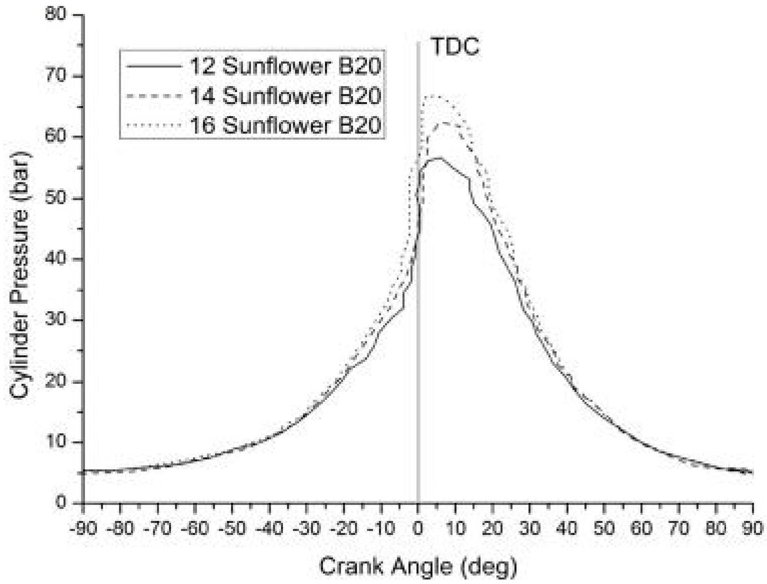


Figure 4.2. Cylinder pressure graph of Sunflower B20

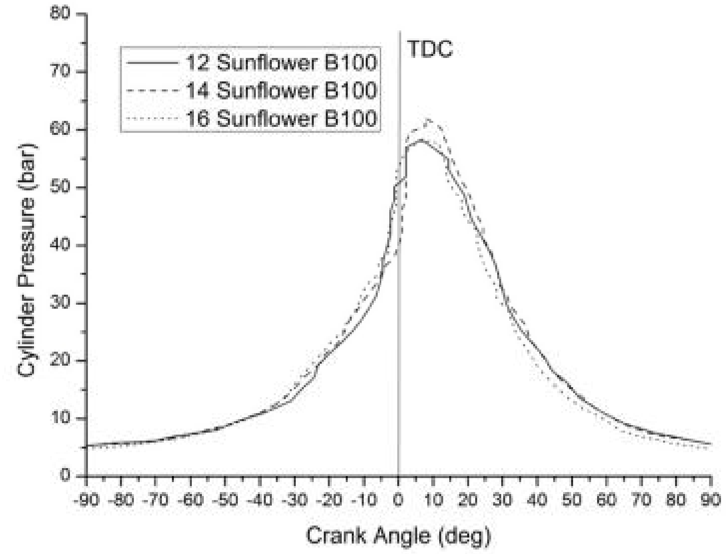


Figure 4.3. Cylinder pressure graph of Sunflower B100

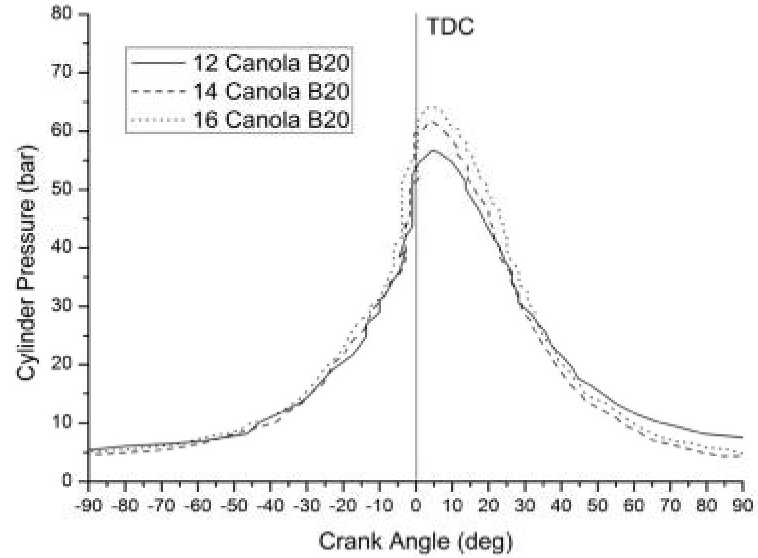


Figure 4.4. Cylinder pressure graph of Canola B20

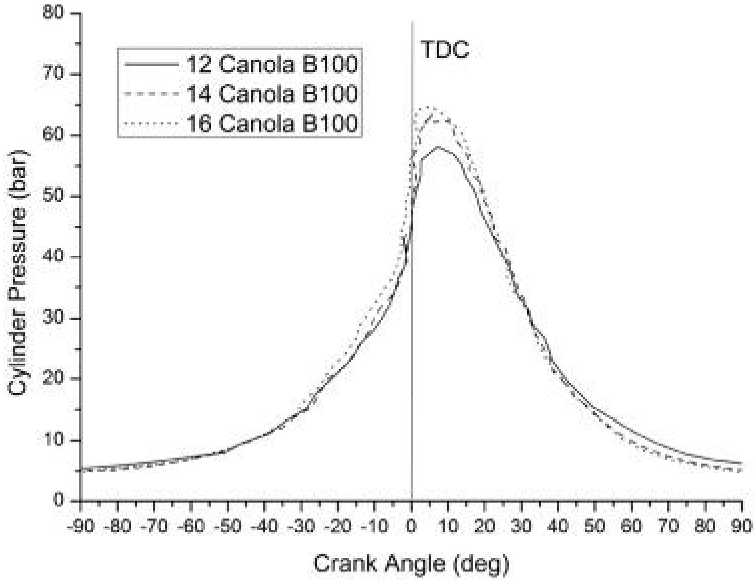


Figure 4.5. Cylinder pressure graph of Canola B100

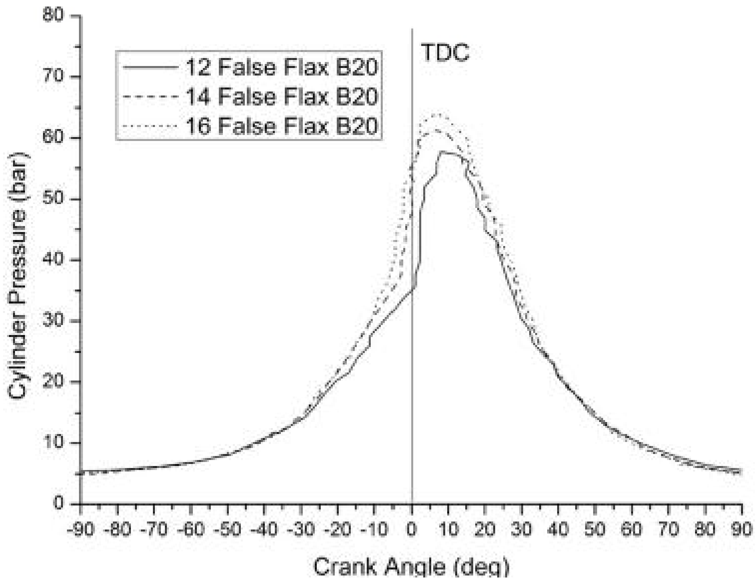


Figure 4.6. Cylinder pressure graph of False Flax B20

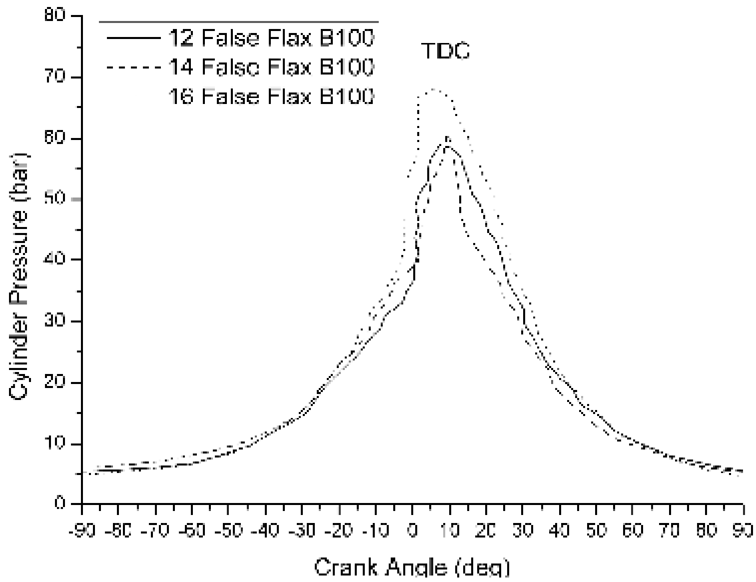


Figure 4.7. Cylinder pressure graph of False Flax B100

4.3. Performance Characteristics

Brake thermal efficiency (BTHE) defined as ratio of engine power output to heat input of fuel is one of the most important performance criteria for internal combustion engines (Paul et al., 2014). Figure 4.8 shows the brake thermal efficiency results of test fuels and Figure 4.9 indicates the specific fuel consumption (SFC) values.

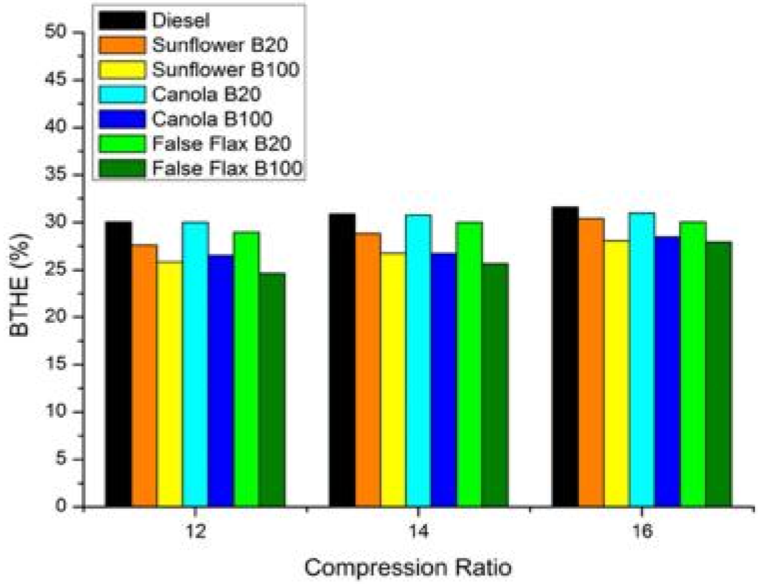


Figure 4.8. BTHE values of all test fuels

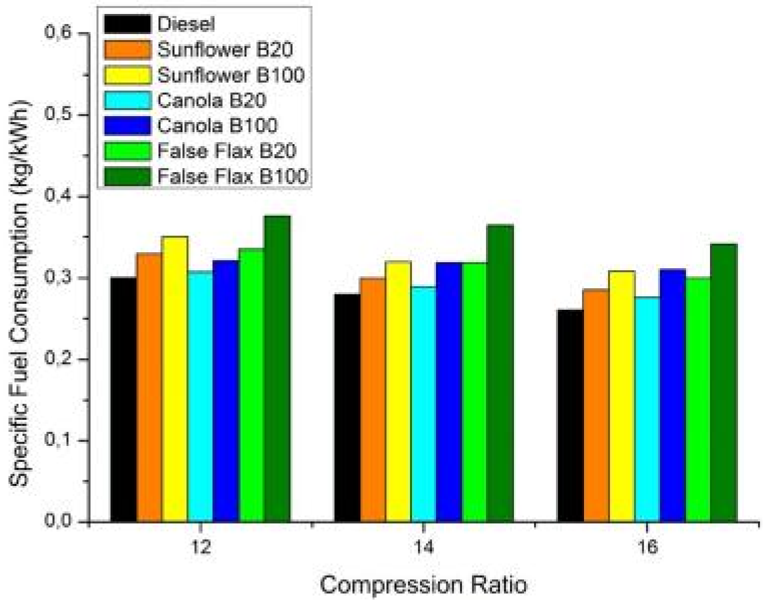


Figure 4.8. SFC values of all test fuels

It can be seen from graphs that increasing compression ratio improved BTHE since higher compression ratio enhances combustion. Biodiesel usage resulted in lower BTHE since biodiesel has lower calorific value than diesel fuel. And also, lower cetane number of biodiesel and diesel-biodiesel blends caused higher ignition delay time which causes prolonged combustion duration. Increasing compression ratio improved BTHE and SFC values for all test fuels. Increasing CR from 12:1 to 14:1 and from 12:1 to 16:1 improved BTHE 2,8% and 5,16% when engine was fuelled with diesel fuel, respectively. The maximum improvement of BTHE occurred with sunflower B20 and false flax B100 fuels and measured as 10,14% and 13,23%, respectively when the CR increased from 12:1 to 16:1. Depending on BTHE, SFC values were also enhanced with CR increment. SFC values were decreased by 6,78% and 13,37% for diesel fuel when the CR increased to 14:1 and 16:1 from 12:1, respectively. The maximum improvement of SFC was with diesel and sunflower B20 fuels and measured as 13,37% and 13,45%, respectively when the CR increased from 12:1 to 16:1. Theoretically, increasing compression ratio provides better combustion and higher brake thermal efficiency. The thermal efficiency for diesel engines is shown in equation 3.

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}\left(\frac{\alpha^{\gamma} - 1}{\gamma(\alpha - 1)}\right) \quad (3.7.)$$

Where;

η_{th} is thermal efficiency,

α is the cut-off ratio (ratio between the end and start volume for the combustion phase)

r is the compression ratio,

γ is ratio of specific heats (C_p/C_v).

Figure 4.9 shows the exhaust gas temperatures (EGT) of experiment fuels. EGT showed a linear relationship with CR increment. Biodiesel usage increased EGT for all compression ratios. This may be due to extra oxygen (O_2) content of biodiesel and depending on this property better combustion of biodiesel. The maximum EGT was measured with false flax B100 fuel at 16:1 CR.

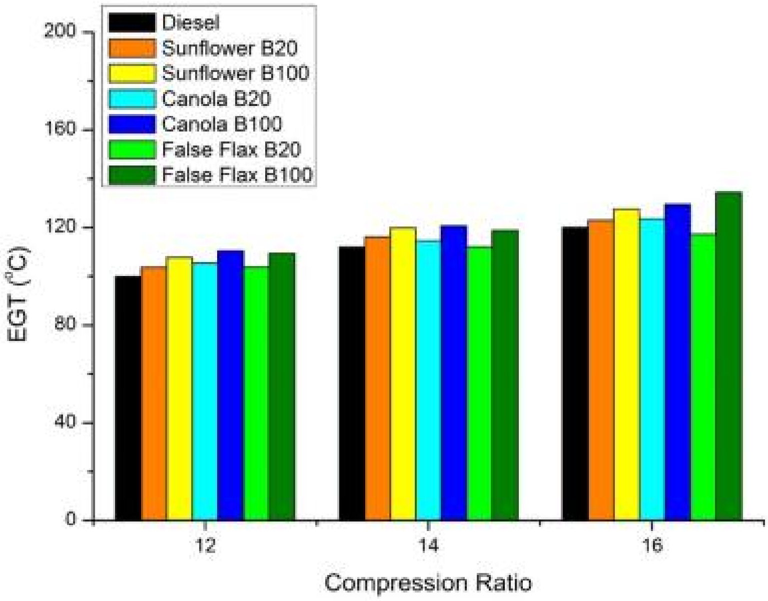


Figure 4.9. EGT values of all test fuels

Table 4.3. Variation of performance values of test fuels with CR increment

Fuel	CR from 12:1 to 14:1 Increment – Decrement (%)			CR from 12:1 to 16:1 Increment – Decrement (%)		
	BTHE	SFC	EGT	BTHE	SFC	EGT
Diesel	2,80	-6,78	12,25	5,16	-13,37	20,25
Sunflower B20	4,49	-9,09	12,18	10,14	-13,45	18,64
Sunflower B100	3,48	-8,57	11,33	8,59	-11,85	18,42
Canola B20	2,58	-5,79	8,83	3,28	-10,18	17,26
Canola B100	0,67	-0,74	9,16	7,46	-3,36	17,05
False Flax B20	3,58	-4,77	8,12	3,71	-10,41	13,01
False Flax B100	4,13	-3,00	8,60	13,23	-9,13	22,86

4.4. Emission Characteristics

CO Emissions**:** Figure 13 shows the CO emission results of the experiments. CO formation is directly related with incomplete combustion of reactants (fuels in-cylinder) and insufficient amount of oxygen (Zhang et al., 2003). It is clear that higher CR provides better combustion and thus lower CO emissions. The test engine emitted lower CO emissions when the CR increased from 12:1 to 16:1 for all test fuels. At 12:1 CR conditions except sunflower B100 and canola B20 fuel, diesel fuel gave better CO emission results compared to other test fuels. This may be due to lower cetane numbers of biodiesel used in experiments. With increment of CR biodiesel and biodiesel-diesel blends resulted with lower CO emissions. Biodiesel fuels contain extra O_2 content in their chemical composition. So, the use of biodiesel enhances the combustion and CO emissions are converted to CO_2 emissions. Increasing CR from 12:1 to 14:1 and 16:1 improved CO emission 11,59% and 42,02%, respectively for diesel fuel. Increasing CR from 12:1 to 14:1 and 16:1 advanced CO emission 18,3% and 50,7% for sunlflower B20, 10,9% and 34,54% for sunflower B100, 11,76% and 35,29% for canola B20, 25,97% and 58,44% for canola B100, 21,25% and 51,25% for false flax B20, 26,02% and 54,79% for false flax B100, respectively. The maximum improvement was obtained with canola B100 fuel in terms of CO emissions.

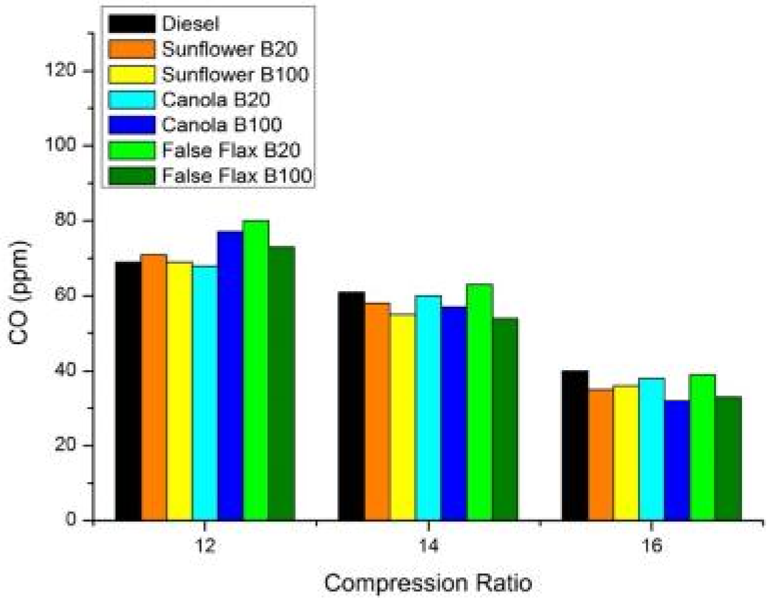


Figure 4.10. CO values of all test fuels

CO_2 Emissions: Variation of CO_2 emissions of experiments are shown in Figure 4.11. It can be seen from the graphs higher CR experiments resulted in higher CO_2 emissions since as CR is increased the combustion is improved and thus CO and unburned hydrocarbon compositions are converted into CO_2 emissions. Also use of biodiesel caused to increase of CO_2 emissions at high CRs. This is an expected phenomenon because carbon molecules are mostly converted to CO or CO_2. As the oxidation gets better, carbon molecules are converted into CO_2 substantially. For diesel fuel, CO_2 emissions were higher 4,16% and 13,97 at CR 14:1 and 16:1, respectively compared to CR 12:1. Increasing CR from 12:1 to 14:1 and 16:1 increased CO_2 emission 17,77% and 37,77% for sunflower B20, 47,05% and 76,17% for sunflower B100, 33,33% and 64,10% for canola B100, 19,56% and 32,6% for false flax B20, 24,44% and 44,44% for false flax B100, respectively. The increment of CR from 12:1 to 16:1 increased CO_2 emission 18,37% but, increasing CR from 12:1 to 14:1 decreased CO_2 emission 5,86% for canola B20 fuel.

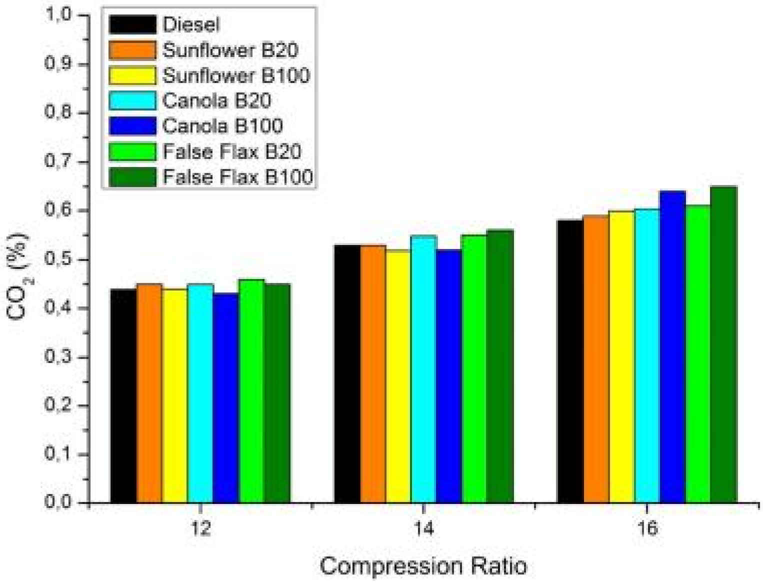


Figure 4.11. CO_2 values of all test fuel

NO_x Emissions: NO_x results of all test fuels are shown in Figure 4.12. Higher CR means higher cylinder pressure and higher cylinder temperature. High cylinder temperatures cause more formation of NO_x emissions. NO_x formation is mainly dependent on end-combustion temperature and flame velocity (Balat, 2007b). Also biodiesel usage increased NO_x emissions since combustion temperature of biodiesels are higher than that of diesel fuel. Experiments revealed that higher CR experiments resulted in higher NO_x emissions. Increasing CR from 12:1 to 14:1 and 16:1 increased NO_x emissions, 6,89% and 12,06% for diesel fuel, 5,04% and 15,96% for sunflower B20, 7,45% and 12,42% for sunflower B100, 10,18% and 31,48% for canola B20, 15,03% and 22,22% for canola B100 11,66% and 20,83% for false flax B20, 4,24% and 16,96% for false flax B100, respectively.

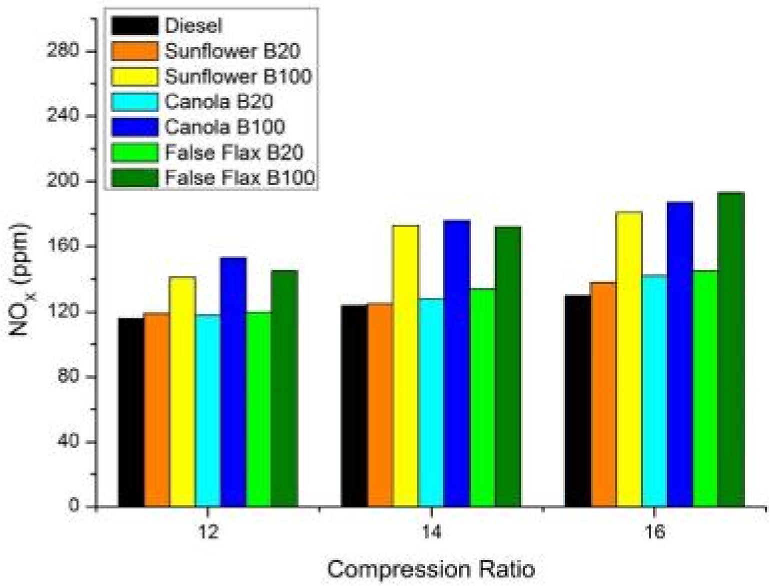


Figure 4.12. NO_x values of all test fuels

4.5. Diesel RK Simulation Software Results

Compression ratio is a critical parameter for internal combustion engines. Since CR directly changes the combustion characteristics of an engine, CR should be chosen as high as possible. Simulation and calculation are very useful tools for predicting the engine performance characteristics without conducting actual experiments. Modelling of an engine makes easier for parametric studies. In this study, addition to experimental study, the experimental engine was modelled with the aid of Diesel RK software. The results of experiments were compared with actual experiments in order to validate experimental data.

Thermal Efficiency Calculation: For a diesel engine, the thermal efficiency is calculated with formula (3.7.) theoretically. Theoretically, thermal efficiency of a diesel engine depends on compression ratio (r), cut-off ratio (α) and ratio of specific heats (γ). The thermal efficiency values of compression ratios used in this study are given in Table 4.4 for typical values of cut-off ratio (α) and ratio of specific heats (γ).

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}\left(\frac{\alpha^{\gamma}-1}{\gamma(\alpha-1)}\right) \quad (3.7.)$$

(η_{th}) = BrakePower/Fuel Energy (3.8.)

$$\eta_{th}(\%) = \frac{BrakePower(kW)\times 3600}{FuelFlow\left(\frac{Kg}{Hr}\right)\times \text{CalorificValue}\left(\frac{\text{Kj}}{\text{Kg}}\right)} \times 100 \quad (3.9.)$$

Where;

η_{th} is thermal efficiency,

α is the cut-off ratio (ratio between the end and start volume for the combustion phase),

c_p is specific heat at constant pressure,

c_v is specific heat at constant volume,

γ is ratio of specific heats (c_p/c_v),

r is the compression ratio.

Table 4.4. Calculated BTHE values

Compression Ratio	**Brake thermal efficiency (BTHE) %**
12:1	45,7
14:1	48,1
16:1	50,1

Where;

γ = 1,3 and α = 2,4

The calculation shows that increasing CR from 12:1 to 14:1 and 16:1 improves thermal efficiency. The calculation results shows that elevating the CR from 12:1 to 14:1 and 16:1, improves BTHE values 5,25% and 9,62%, respectively. The calculation results and experimental results shows significant difference since the calculation is only based on theoretical ideal diesel cycle. Even though the significant difference between the theoretical calculation and actual values of BTHE, the trend of variation of BTHE when the CR is changed is in good agreement for both calculation and experimental results.

Simulation Results: In the simulation, the experimental engine was modelled and three different fuel used in experiments were used as fuel. BTHE results of diesel fuel, false flax B20 fuel and false flax B100 fuel showed similar trend with the experimental results. The simulation showed that increasing CR resulted with higher BTHE and lower SFC. Figure 4.13 shows the experimental and simulation results of the diesel fuel. Compared to experimental results BTHE values showed 5,90%, 6,80% and 6,98% difference for 12:1, 14:1 and 16:1 CRs, respectively. Simulation results are in good agreement with the experimental study.

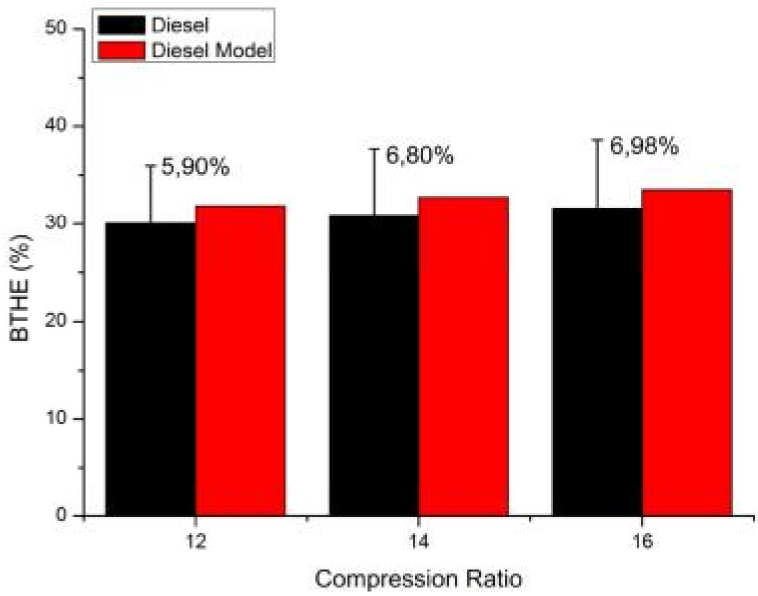


Figure 4.13. BTHE values of diesel engine (experimental and model)

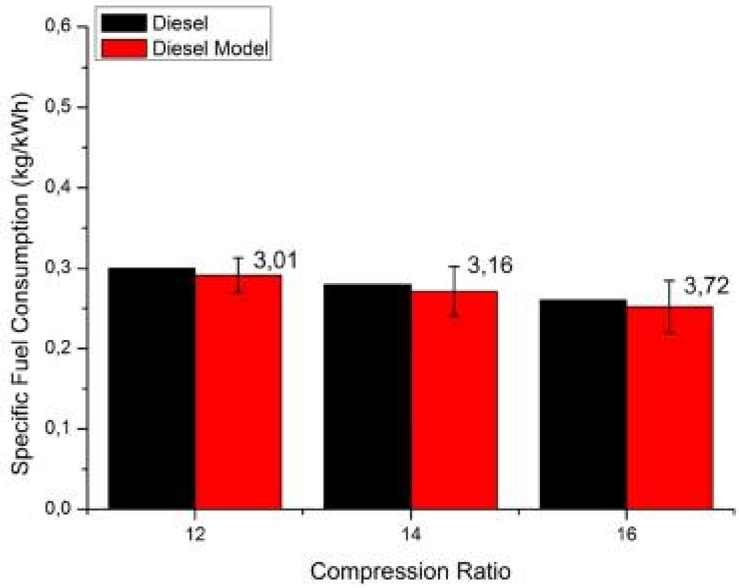


Figure 4.14. SFC values of diesel engine (experimental and model)

Figure 4.15 - 4.18 shows the comparison of BTHE, SFC, CO and NO_x values of experimental and modelling results for diesel, false flax B20 and false flax B100 fuels. The simulation showed that increasing CR improved BTHE for all test fuels as it is expected. Better fuel economy was obtained due to higher CR ratio. SFC results showed that increasing CR provides better combustion and thus lower CO emissions. Also, increasing CR enhanced combustion and so NO_x values were increased with CR increment. Furthermore, according to simulation, NO_x values were higher when false flax B20 and false flax B100 fuels simulated as it is expected.

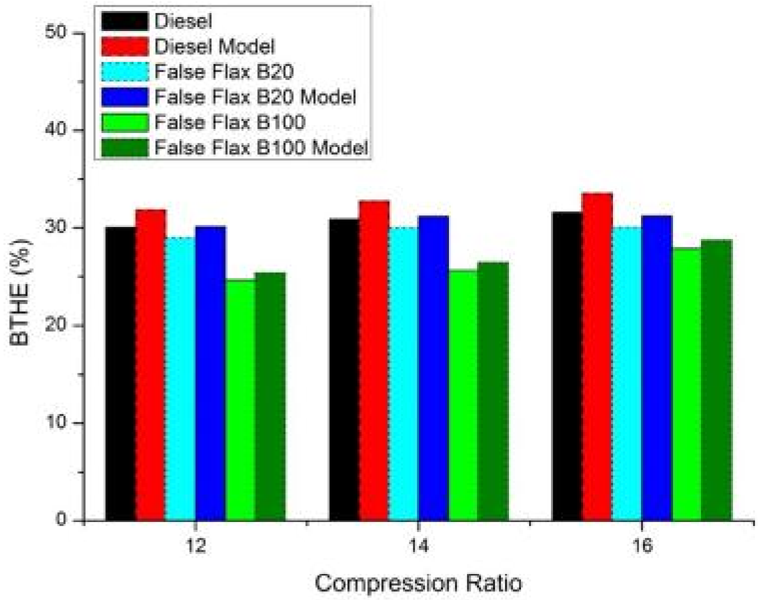


Figure 4.15. BTHE values of test fuels (experimental and model)

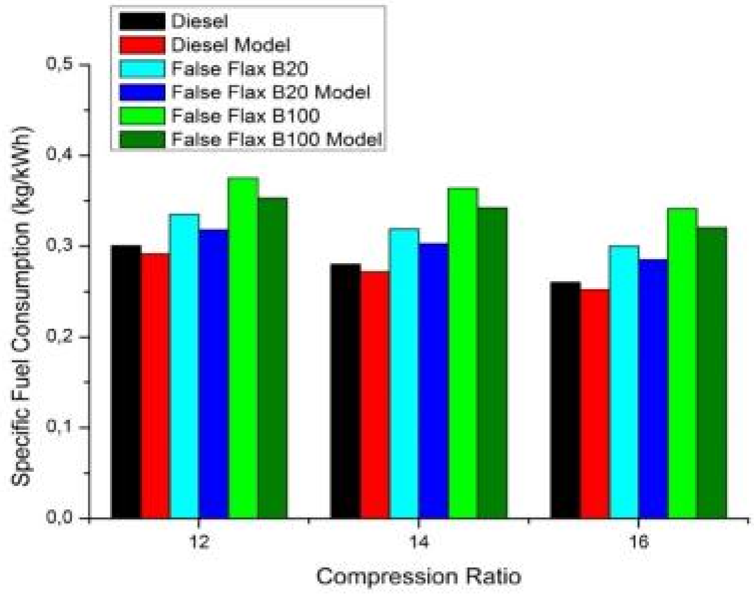


Figure 4.16. SFC values of test fuels (experimental and model)

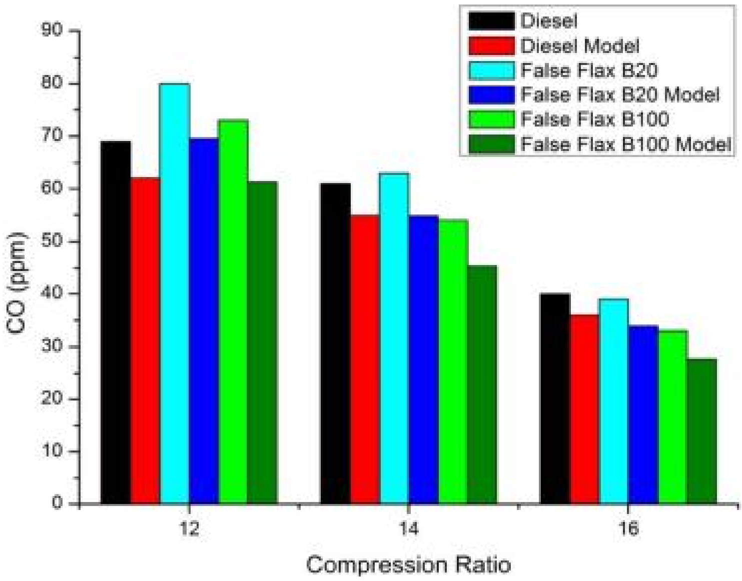


Figure 4.17. CO values of test fuels (experimental and model)

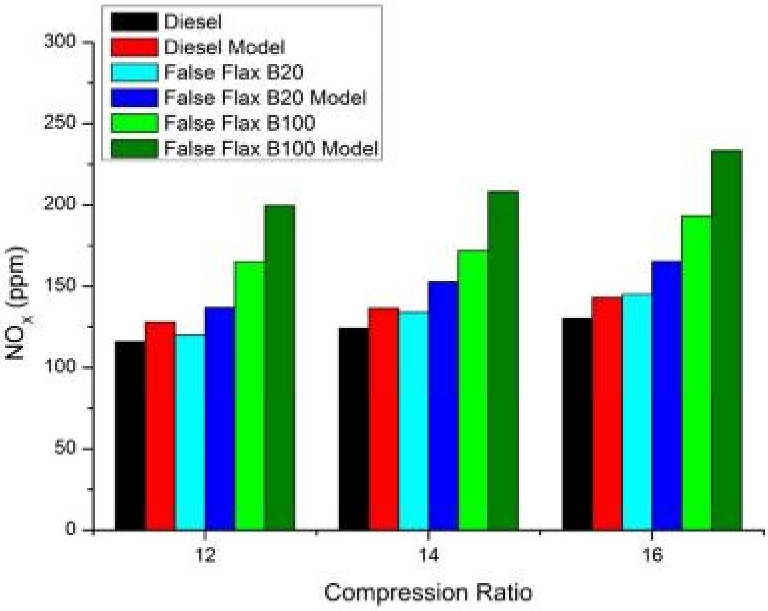


Figure 4.18. NO_x values of test fuels (experimental and model)

5. CONCLUSIONS

This study was carried out in order to find out the performance, combustion, and emission characteristics of a diesel engine at various compression ratios fuelled with diesel, biodiesel, and diesel-biodiesel blend B20) fuels. During the experiments the engine compression ratio was set as 12:1, 14:1, and 16:1. According to test results, the followings can be summarized;

- The increment of CR improved thermal efficiency and specific fuel consumption values for all test fuels.
- Maximum BTHE (31,6%) was obtained at 16:1 CR when engine was fuelled with low sulphur diesel. Biodiesel blend (B20) and biodiesel (B100) usage caused decrement of BTHE values compared to diesel fuel.
- Increasing CR resulted with higher cylinder pressure and better combustion.
- With the increment of CR ignition delay of all fuels were shortened and the combustion occurred near to TDC.
- Higher CR experiments resulted with lower CO emissions due to better combustion and thus higher CO_2 emission was observed.
- Due to increased cylinder temperature NO_x values were increased when engine was operating with higher CRs.
- Biodiesel usage further increased NOx emission due to extra oxygen content in the molecular structure but also, biodiesel usage improved CO emission values.
- Increasing CR improved SFC due to better BTHE for all test fuels. Compared to diesel fuel diesel-biodiesel blends and biodiesel fuels increased SFC slightly.
- Exhaust gas temperature was increased with higher CR and biodiesel usage

- Modelling of engine and fuels showed similar trends with the experimental results. BTHE values were increased and SFC values were decreased with CR increment according to simulation results.

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