ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

School of Mechanical, Chemical and Materials Engineering

Production of Liquid Fuel from Waste Tyre and Testing the Performance in Diesel Engine

A thesis submitted in partial fulfillment of

the requirements for the award of the degree of master of science

in

Automotive Engineering

By

Melaku Fitsum

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DEPARTMENT OF MECHANICAL AND VEHICLE ENGINEERING

September, 2018

ADAMA

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "**Production of Liquid Fuel from Waste Tyre and Testing the Performance in Diesel Engine**" in partial fulfillment of the requirements for the award of the degree of master of science in automotive engineering is an authentic record of my own work carried out from February 2017 to February 2018 under the supervision of N.Ramesh Babu (Asst. Professor) and Mr. Deresse Feriew (thesis Co-advisor).

The matter embodied in this thesis has not been submitted by others for the award of any other degree or diploma. All relevant resources of information used in this thesis have been acknowledged.

Melaku Fitsum _____ 18/10/2018

Candidate Signature Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge and belief. This thesis has been submitted for examination with my approval.

N.Ramesh Babu (Asst. Professor) _____ 19/10/2018

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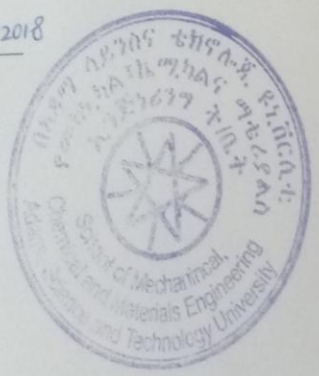

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ACKNOWLEDGEMENT

In the path of my thesis, I have received invaluable help from a number of people without whom I would have floundered about aimlessly. First and foremost I would like to thank God for keeping me sane and enabling me carry out for letting me finish my project without many hindrances.

My deepest appreciation goes to my advisor N.Ramesh Babu (Asst. Prof), for his excellent guidance, suggestions and constructive criticisms and valuable suggestion throughout this thesis work and for his support in finalizing the thesis. I would like to express my gratitude to Mr. Idris I. (Head of the Department) and Mr. Deresse Feriew (thesis Co-advisor), for their valuable suggestions and encouragements at various stages of the work.

I would like to thank the Hang WaTyre oil industry factory, Addis Abeba petroleum supply Enterprise, ASTU automotive mechanical and vehicle engineering lab assistants and Chemical department of Adigrat University for taking their time out of their normal schedules to solve my thesis requests and for their sponsoring and subsidizing my research activities to accomplish fit tolerably.

Last but not least, I am highly indebted to my family and friends for their wisdom, financial support, encouragement and for bringing me up with love & confidence throughout the writing of this paper. Words cannot express the magnitude of my gratitude to them.

Generally, I would like to extend my gratitude for all the above people and those whose names are not mentioned here but contributed their part a lot towards the success of this research.

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ACRONYMS, SYMBOLS AND ABBRIVATIONS

NO_X	Oxides of Nitrogen
CO	Carbon mono oxide
HC	Hydro Carbon
C	Carbon
CO_2	Carbone Dioxide
HHV	Higher Heating Value
LHV	Lower Heating Value
NR	Natural Rubber
SBR	Styrene Butadiene
PB	Poly Butadiene
WPF	Waste Plastic Fuel
CI	Compression Ignition
CN	Cetane Number
CI	Cetane Index
IC	Internal Combustion
PM	Particulate Matter
Bsfc	Brake Specific Fuel Consumption
Sfc	Specific Fuel Consumption
$\dot{m}_f$	Mass Flow Rate of fuel flow

N	Engine Speed
n_{th}	Thermal Efficiency
T_b	Brake Torque
T_w	Torque at rear wheels
P_b	Brake Power
GC	Gas Chromatography
MS	Mass Spectrometer
BP	Boiling Point
DF	Commercial automotive Diesel Fuel
LPG	Liquefied Petroleum Gas
CNG	Compressed Natural Gas
USP	Ultrasonic Spray Pyrolysis
MTPO	Modifications of Tire Pyrolysis Oil
ELT	End of Life Tires
RMA	Rubber Manufacturers Association
TDF	Tire Derived Fuel
USP	Ultrasonic Spray Pyrolysis
FID	Flame Ionization Detector
TQT	Thermo-Quest-Trace
GCV	Gross Calorific Value

FVP	Flash Vacuum Pyrolysis
FBR	Fixed Bed Reactor
ASTM	American Standard for Testing & Materials
API	American Petroleum Institute
TPO	Tyre Pyrolysis Oil
DTPO	Distillated Tyre Pyrolysis Oil
CB	Carbon Black
HTOIF	Hang Wa Tyre Oil Industrial Factory

ABSTRACT

Scrap tyre is considered to be one of the very common and significant solid wastes and its production is increasing due to the increased number of vehicles in both developed and developing countries. Initiatives are being taken to overcome the fossil fuel crisis by looking for alternatives to replace gasoline and diesel fuel. This thesis aims the production of liquid fuel from waste tyres pyrolysis and studying the characterization of the produced fuel similar to conventional diesel fuel and its utilization in diesel engine. The importance of doing this study is to find out ways to recycle the waste tyres into products to reduce the amount of waste tyres in Ethiopia. Recycling provides a sustainable source of materials by processing a priority waste so that it can enter into a new cycle of life-extending the functional values. In this context pyrolysis of scrap tyres can be used effectively to produce oil, thereby solving the problem of waste tyre disposal. As these are the non-renewable resources it is difficult to predict availability of these resources in future, resulting in uncertainty in its supply and price and is impacting growing economies due to this many attempts have been made by different researchers to find out alternate fuels for Internal Combustion engines. This thesis focuses on the performance characteristics of diesel engine using liquid fuel distilled from tyre oil blended with diesel fuel. In this work, crude oil from waste tyre is obtained using pyrolysis method at temperature range of 800-900^{0}C and the tyre diesel oil is produced using a process called distillation. The exact & appropriate reaction temperature range of 200-270 ^{0}C was reached the distillation. Fuel properties of the pyrolytic distilled oil and blended oil were analysed with ASTM. Performance analysis is done on chassis dynamometer on four stroke, four cylinder diesel -engine. Brake power, brake torque and brake specific fuel consumption of produced diesel blends shows similar pattern with slight reduction of brake power and torque as the blend ratio increased as compared to that of diesel fuel on performance test result.The selected important properties of the diesel were measured and all this properties are in the limits of the test standard for all blends of the diesel tested. The blended of the tyre diesel in this work uses a mixture of liquid tyre oil and diesel fuel with volumetric compositions of liquid tyre oil: ADO (B0): DTPO (B100), and 20% DTPO: 80% ADO (B20).

Keywords: waste tyre, recycling, pyrolysis, distillation, tyre oil diesel, performance test and emission test.

1. INTRODUCTION

1.1. Background

A **tyre** is an organic solid plastic, essentially a polymer or combination of polymers of high molecular mass. A polymer is a chain of several thousand of repeating molecular units of monomers. It is made up of natural rubber or synthetic rubber or a combination of natural and synthetic rubber, whether new, used or re-treaded. It is made of the following compounds which are rubber, carbon black, silica, metal, textile, zinc oxide, Sulfur, copper compounds, cadmium, lead and lead compounds, organic halogen compounds and some additives like solvents, age resistors, vulcanizing agents, softeners, fillers and processing aids in varying proportions depending on whether it is a car or truck tyre [Forrest, 2014; Stefano et al. 2014].

A typical tyre may contain up to 30 different types of synthetic rubber, 8 different natural rubbers, in addition to a range of different carbon black fillers and up to 40 different additive chemicals. The main rubber types used are, typically, styrene– butadiene-rubber, natural rubber (poly-isoprene), and poly-butadiene rubber [Rodriguez et al. 2001; Chen et al. 1995].

Apart from energy and carbon material production, a wide range of materials which are illustrated in Table 1 can be recovered.

Table 1: Typical composition of vehicle and truck tires [Isabel, 2001].

Component	Vehicle tire (wt. %)	Truck tire (wt. %)	Comments
Rubber	47	45	e.g. styrene, butadiene rubber, natural rubber and nitrile rubber
Carbon black	21.5	22	Used to strengthen the rubber and aid abrasion resistance
Metal	16.5	21.5	Steal belts and cord for strength
Textile	5.5	—	Used for reinforcement
Zinc oxide			Used (with stearic acid) to control vulcanization process

	1	2	and to enhance the physical properties of the rubber
Sulfur	1	1	Used to cross link the polymer chains within the rubber and also to harden and prevent excessive deformation at elevated temp.
Additives	7.5	5	e.g. Clay or silica used to partial replacement of carbon black

A ***waste tyre*** also known as End-of-Life Tyres (ELT), are used rubber tyres that because of their abrasion state ("tire wear") are not safe for public traffic. Waste tyres can go into tyre recycling or will be dumped, either in legal landfills or illegally; another portion may be pyrolysis to produce tyre-derived fuel or heat energy [Ramos et al. 2011].

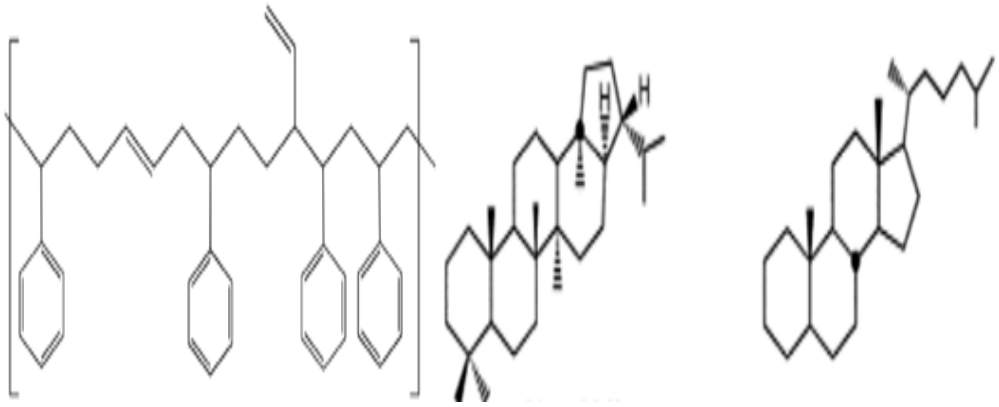


Fig. 1: polystyrene molecular structure Waste tyre structure [Ramos et al. 2011].

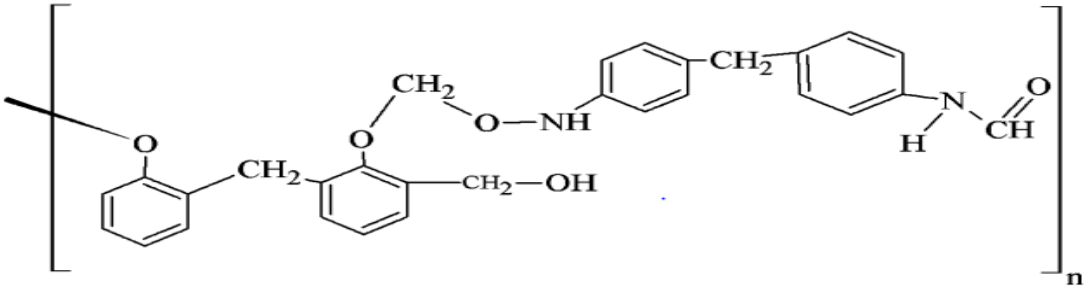
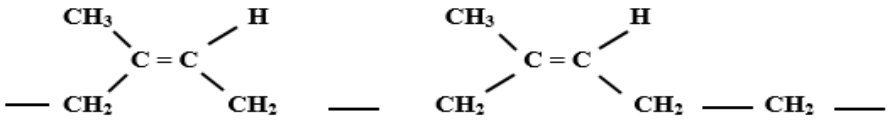
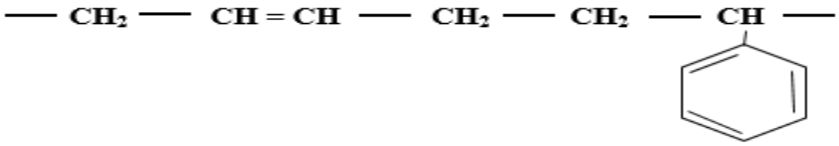


Fig. 2: Monomer precursor of the polymeric resin [Williams &Bottrill, 2013].

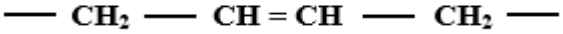
(a) Natural Rubber (NR):



(b) Styrene-Butadiene Rubber (SBR):



(c) Butadiene Rubber (BR):



(d) Formation of polycyclic aromatic hydrocarbons:

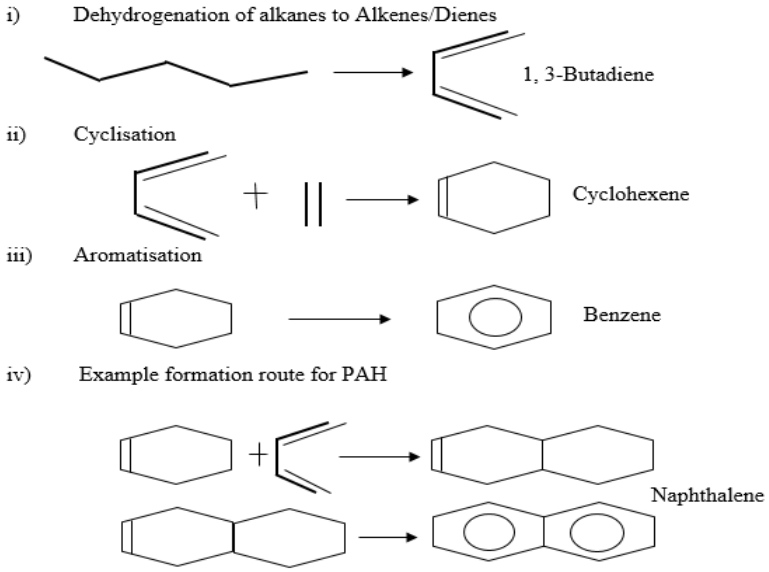


Fig. 3: Rubber structure and the formation of polycyclic aromatic hydrocarbons [Williams & Bottrill, 2013].

Waste tyres are generally discarded after only a small amount of rubber is worn away. Even so, these tyres are unfit for further use in the vehicles they were made for. At the same time they are also unwelcome in landfills and have been proven to be an environmental threat. Whole tyres can be used for a number of applications, including artificial reefs, breakwaters, erosion control, playground equipment, and highway crash barriers. Due to the sheer volume of disposable tyres, they take up a great deal of valuable space in landfills. In addition, they have been known to bubble to the surface of landfills as they tend to trap methane gas. This bubbling can contaminate local water systems, as it can damage the landfill liners that are meant to control contaminants [RMA, 2009].

Since the inability for landfills to provide adequate space for tire disposal, other forms of disposal and reclamation have been put into place, using waste tyres as both commodities (new tyres) as well as a form of energy (fuel alternative).The automobile has become an indispensable means of transportation for many households throughout the world. Thus, the disposal of vehicle tyres represents a major environmental issue throughout the world. Worldwide, almost 1 billion tyres for passenger cars, utility vehicles, trucks, off-road vehicles, etc. are manufactured each year. Every year an almost equal number of tyre is permanently removed from vehicles and defined as waste. With heavy consumption of fossil energy and fuels, the world is facing with shortage of energy and environmental concerns which may aggravating in the future if no other solutions are found. On the other hand, renewable energy sources and waste streams can be processed for production of energy and fuels. Pyrolysis of waste tyre is an economical method to solve waste tyre problem and to produce quality liquid fuel which is having similar properties to the commonly used petroleum fuels. The disposal and reprocessing tyres are difficult since they contain complex mixture of different materials such as rubber, carbon black, steel cord and other organic and inorganic minor components There are major aspects of tyre problems such as tyres stock piles provide Breeding ground for mosquitoes and vermin, this in turn, causing serious disease and affecting human health [RMA, 2005].

1.2. Statement of the Problem

Even with laws in place, illegal dumping still occurs, presenting negative environmental impacts. The dumping of tyres is a problem in most local areas of Ethiopia. Most people think that the best way to dispose scrap tires is to burn them or throw them in dumpsites but this creates environmental strain. The opportunity to make use of used tyres is rarely appreciated.

Recycling of scrap tyres on a global scale can drastically reduce waste yards, soil and atmospheric contamination caused by dump yards and large scale tyre fires. And this recycling goes hand in hand with design for pure environmental conditions because it aims at generating minimum waste during the product lifecycle in case of use and disposal systems.

And this study will extremely give the answer for the following questions

- Are the properties of fuel produced from waste tyre similar to the conventional diesel fuel?
- Is the fuel produced suitable for running the Diesel Engine?

1.3. Objectives of the Study

1.3.1. General Objective

The general objective of this study is to produce a liquid fuel from waste tyre and testing the performance of the produced fuel in diesel engine.

1.3.2. Specific Objectives

The specific objectives of this study are:-

- To produce diesel fuel from the produced waste tyre oil.
- To measure characteristic parameters of the fuels such as Reid vapor pressure, distillation, total sulfur, viscosity, density, cloud point, flash point, carbon residue, color, water sediment, ash content, and total acidity of the fuel produced.
- To test the waste tyre oil fuel produced in diesel engine.
- To study and compare the performance characteristics of the produced fuel with diesel fuel

1.4. Significance of the Study

- This study will show the possibility of extracting liquid oil from used tyres.
- This study will show the possible use of extracted liquid tyre oil for running diesel engine.

- **Environmental Benefits**

This study will guide to help for our environmental situation to consider the tribulations and in the process of developing waste tyre regulations that would be expected to:

- Control the stockpiling
- Control illegal dumping
- Regulate storage

- Provide guideline for the management of waste tyre facilities, e.g. waste tyre storage sites, waste tyre recycling sites, etc.

Since the presence of waste tyre in land fill can cause poor air quality because it is not biodegradable, it can remain for long period of years. Therefore, the process can minimize this problem and the process does not create any pollution.

- **Economic Benefits**

The developed technology will prove to be beneficial to the country for the purpose of catering increasing demand of fuel / energy and will save millions of foreign exchanges.

This conversion shall lead to the development of simple and economically viable technology for environment friendly disposal of wastes. Increased utilization of a fuel obtained from waste tyre results in significant microeconomic benefits to both the urban and rural sectors, and the balance of trade.

- ♦ Production of fuel from waste tyre can help close the trade gap by substituting imported petroleum.
- ♦ To reduce petroleum import bills and secure oil fuel supply.

Particularly fuel extraction from waste tyres will use as an alternative energy solution to petroleum oil response mechanism.

1.5. Scope of the Study

This study is delimited to the production of liquid fuel from waste tyre available in Ethiopia using pyrolysis and studying the properties of produced fuel similar to diesel and testing in diesel engine.

1.6. Limitations

In the country there is a shortage of skilled manpower in the field of pyrolysis of waste tyre material. There is only one dedicated tyre pyrolysis plant in the local city of Ethiopia that is operating on a semi-commercial basis. It is owned by Chinese private company. It was a big challenge to locate and find the functional details about the plant.

Due to non-availability of testing equipment cetane number and calorific value of the produced fuel were not measured.

2. LITERATURE REVIEW

2.1. Overview

2.1.1. What is Waste Tyre?

Tyres are synthetic solid organic materials. They are typically of high molecular mass with a very large molecule made up of smaller units called monomers which are joined together in a chain by a process called polymerization. The polymers generally contain carbon and hydrogen with, sometimes, other elements such as oxygen, nitrogen, chlorine or fluorine.

With the fast development of the society, the amount of the waste tyres is larger and larger. In recent years, the tyre pyrolysis technology has also been developed. The recycled waste tyres are mainly used to make de-vulcanized rubber and rubber powder. However, producing the de-vulcanized rubber costs a lot of energy, and causes pollution. So there is a new method, pyrolysis technology. The pyrolysis technology is mature in recent years, and doing waste tyre pyrolysis plants adopt the latest pyrolysis technology, and the pyrolysis plants can be used in oil sludge treatment, plastic pyrolysis, tyre treatment and so on.

Wastes of motor vehicle tyre will collect from local city and collected from local collision centre. The collected waste tyre will be sorted out manually and washout using laboratory sink and it will be cut into small pieces for liquefaction process.

Un recycled tyre waste is an enormous global problem because of their non-biodegradability, their flammability and their chemical composition that leads to leaching of toxic substances into the ground on dumping and hazardous fumes on incineration. Since they are heavy, thick, and made of multiple materials, scrap tyres present distinct challenges in recycling and disposal [Williams, 2013].

According to the Rubber Manufacturers Association (RMA), as reported elsewhere,

- 52% of scrap tires are burned for fuel
- 12% are used in crumb rubber products
- 16% is used for civil engineering applications at least 14% is ground and dumped in landfills

Waste or Scrap tyres are made out of a material which can have no economic end use. This means that tires which are no longer suitable for use on vehicles due to wear or damage, can be recycled to serve a new economic purpose (rubber asphalt and concrete, fuel alternatives,

carbon sources, etc. Nearly the entire amount of rubber is discarded, and a valuable resource is left to become an environmental pollutant, if left to be disposed of. It is for this reason that waste tyres must be viewed not only as an environmental issue, but also as an economic benefit [BSG-Bangladesh, 2008].

2.1.2. Target Tyre Waste

Tyre wastes are the most promising resources for fuel production because of its high heat of combustion and due to the increasing availability in local communities. Unlike paper and wood, tyre plastics do not absorb much moisture and the water content of tire waste is far lower than the water content of other wastes.

The conversion method of waste tyre into fuel depends on the rubber type to be targeted and the properties that might be used in the process. Additionally the effective conversion requires appropriate technologies to be selected according to local economic, environment, social and technical characteristics. To get effective conversion from the waste tyre it is most important to select non-hazardous, combustible and suitable feedstock. Because some waste contain undesirable substances such as nitrogen, halogens, and sulfur with flame-retardants additives such as bromine antimony compounds [Rodriguez et al. 2001].

2.1.3. Tyre-Derived Fuel

Tyre-derived fuel (TDF) is composed of shredded scrap tyres. Tyres may be mixed with coal or other fuels, such as wood or chemical wastes, to be burned in concrete furnaces, power plants, or paper mills. With the exception of zinc emissions, potential emissions from TDF are not expected to be very much different from other conventional fossil fuels, as long as combustion occurs in a well-designed, well-operated and well-maintained combustion device [Akyildiz et al. 2012].

Tyre derived fuel is usually consumed in the form of shredded or chipped material with most of the metal wire from the tyre's steel belts removed. The analytical properties of this refined material are published in TDF Produced from Scrap tyres with 96+% Wire Removed.

Tyres are typically composed of about 1 to 1.5% Zinc oxide, which is a well-known component used in the manufacture of tyres and is also toxic to aquatic and plant life. The chlorine content in tyres is due primarily to the chlorinated butyl rubber liner that slows the leak rate of air. The Rubber Manufacturers Association (RMA) is a very good source for compositional data and other information on tyres. The use of TDF for heat production is controversial due to the possibility for toxin production. Reportedly, polychlorinated di-benzo

dioxins and furans are produced during the combustion process and there is supportive evidence to suggest that this is true under some incineration conditions. Other toxins such as NOx, SOx and heavy metals are also produced, though whether these levels of toxins are higher or lower than conventional coal and oil fired incinerators is not clear [Williams, 1998].

On one hand, some argue that it is better to use the energy stored in a tyre than to put it in a landfill, in line with the waste hierarchy. On the other, it is difficult to justify introducing toxins into the atmosphere, and much energy can be saved by recycling the tires so that new ones do not need to be remanufactured from raw materials.

2.1.4. Existing Conversion Technologies for Fuel Production

Conversion technology of waste tyres to fuel is related to chemical recycling process or de-polymerization process. De-polymerization process converts synthetic solid materials into smaller molecules. It can result in a very profitable and sustainable industrial scheme, providing a high product yield and minimum waste.

The experimental setup procedure shown in the figure 4 is the full setup of a close system under laboratory fume hood. For experimental purpose ferric carbonate used as catalyst where as sodium hydroxide, silver nitrate and sodium bicarbonate is used for gas cleaning purpose. Sodium hydroxide, sodium bicarbonate and silver nitrate solution normality was 0.5 (N), 0.25 (N) and 0.25 (N). For waste motor vehicle tyres to fuel production experimental setup purpose accessories and instruments are required such as glass reactor, temperature controller, condensation unit, collection tank, fuel purification unit, final fuel collection tank, residue collection container, liquid solution container and small pump etc. All accessories and part will be connected and tighten enough to prevent gas lose during mixed waste tyre to fuel production.

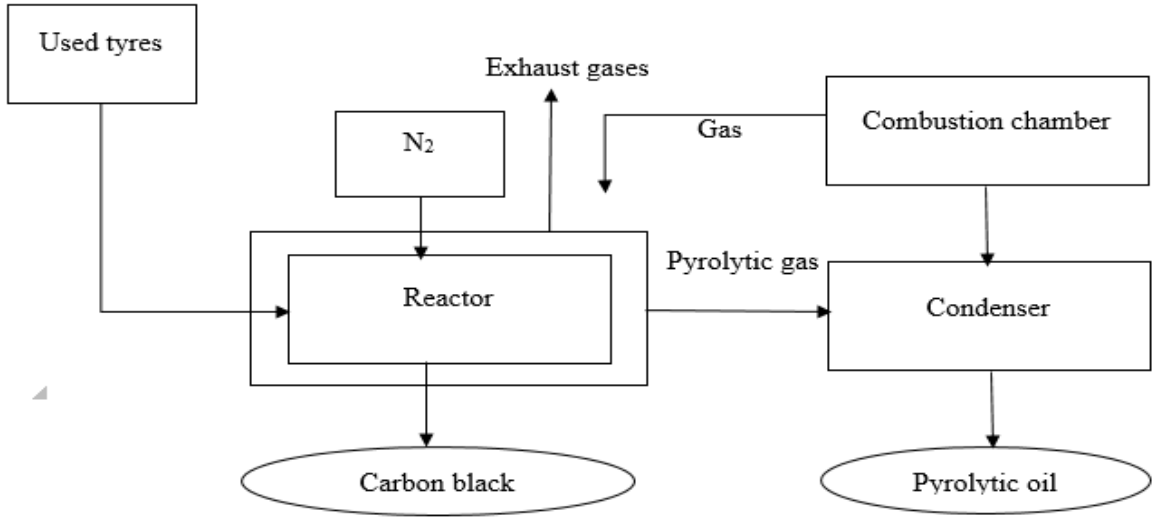


Fig. 4: Experimental setup of waste tyre to fuel production process [Williams, 1998].

Thermolysis is mainly used to produce different kinds of fuel products from de-polymerization process. Thermolysis is a method where decomposition depends under controlled temperature.

Thermo-lysis method can be divided into pyrolysis, hydrogenation and gasification process.

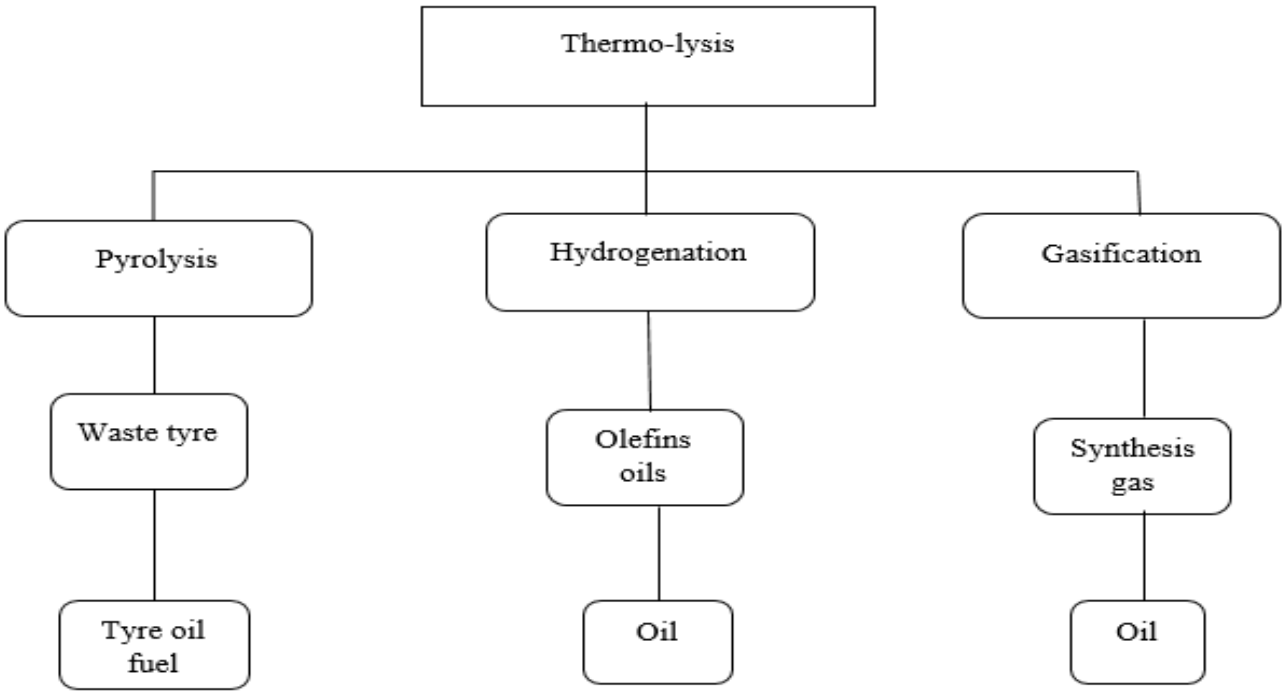


Fig. 5: Different thermolysis schemes with reference to the main technologies [Williams, 2013].

2.2. Pyrolysis

Pyrolysis is an endothermic process, an environmentally attractive method for the treatment of tire wastes. The process uses medium temperatures (300 - 700)^{0}C and high temperature (800-3000)^{0}C and an oxygen-free environment to decompose solid tire wastes chemically in to char, oil, and gas. And it is a thermo chemical decomposition of organic material at elevated temperatures in the absence of oxygen (or any halogen). It involves the simultaneous change of chemical composition and physical phase, and is irreversible. The word is coined from the Greek-derived elements pyro "fire" and lysis "separating" [Rodriguez, 2001].

Fig. 6: Working process of continuous waste tyre pyrolysis plant [Rodriguez, 2001].

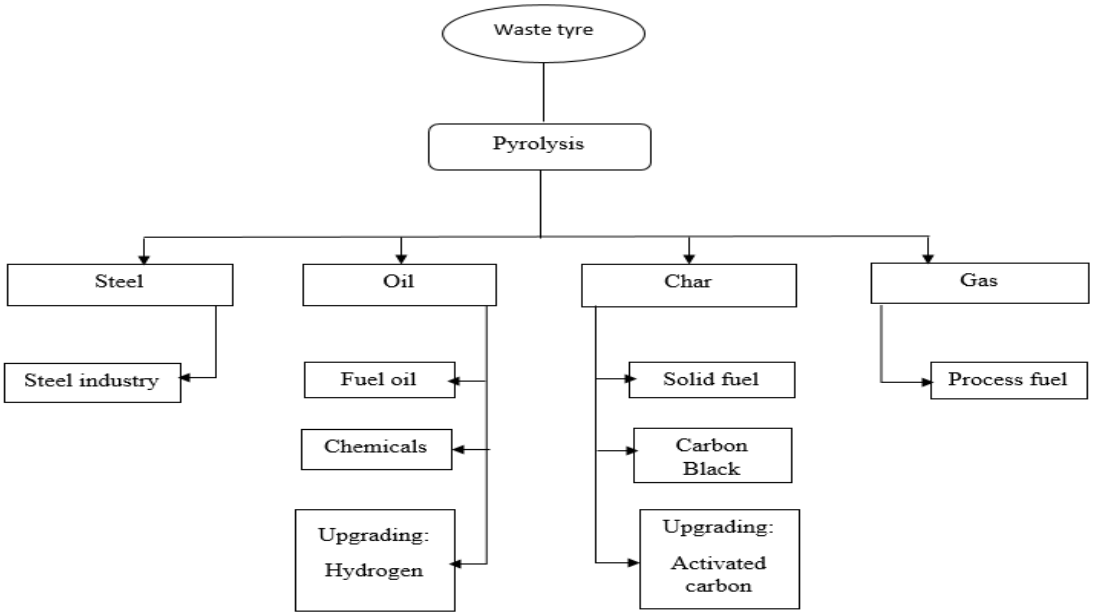


Fig. 7: Pyrolysis process [Rodriguez, 2001].

Pyrolysis is a type of thermoslysis, and is most commonly observed in organic materials exposed to high temperatures. It also occurs in fires where solid fuels are burning or when vegetation comes into contact with lava in volcanic eruptions.

In general, pyrolysis of organic substances produces gas and liquid products and leaves a solid residue richer in carbon content, char. Extreme pyrolysis, which leaves mostly carbon as the residue, is called carbonization.

Pyrolysis differs from other processes like combustion and hydrolysis in that it usually does not involve reactions with oxygen, water, or any other reagents. In practice, it is not possible to achieve a completely oxygen-free atmosphere. Because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs [Dhar and Agarwal, 2014].

2.2.1. Pyrolysis Types and Reactor Configuration

There are many classifications of types of pyrolysis depending on the operating conditions, such as the heating rate, temperature, and the gases residence time. In general, pyrolysis is classified as either fast or slow. Regarding the environment used in the process, it can be classified as oxidative pyrolysis, steam pyrolysis, hydro pyrolysis, catalytic pyrolysis and vacuum pyrolysis, and also depending on the heater system as the microwave or plasma pyrolysis. Conventionally, fluidized and entrained bed reactors are associated with fast pyrolysis whilst fixed bed reactors (FBR) are associated with slow pyrolysis (a batch or semi-batch process).

Other types of reactors such as the rotating cone (usually used for liquid production since the heating rate is high and the vapor residence time is relative short), may also be categorized as carrying out fast pyrolysis [Scheirs and Kaminsky, 2006].

The different methods of pyrolysis processes are discussed in the following subsections.

2.2.1.1. Based on Nature of Pyrolysis

i. Vacuum Pyrolysis

In this process, organic material is heated in vacuum to reduce its boiling point and also to avoid adverse chemical reactions. Flash Vacuum Pyrolysis (FVT) is a process of vacuum pyrolysis in which the residence time of the substrate at working temperature is limited as much as possible, again to minimize secondary reactions. Vacuum Pyrolysis has been investigated on different materials by C. Roy et al [Williams and Besler, 1995; Zhang et al. 2008].

ii. Flash Pyrolysis

In flash pyrolysis, the biomass is ground into fine particles and the insulating char layer that forms at the surface of the reacting particles is continuously removed. Flash pyrolysis is characterized by moderate temperatures exit (400-900) ^{0}C and rapid heating rate (>2^{0}C/s). Vapor residence times are usually less than two seconds. Compared to slow pyrolysis, considerably less tar and gas are produced. However, the tar and oil products are maximized [Besler et al. 1995].

iii. Fluidized Bed Pyrolysis

In this process pyrolysis is done on a fluidized bed which is created by placing a certain quantity of a solid particulate substance in under appropriate conditions to cause the solid/fluid mixture to behave as a fluid [William and Besler, 1995].

2.2.1.2. Based on Residence Type

a. Slow Pyrolysis

This type of pyrolysis, as the name suggests, considers a slow thermal decomposition at low temperatures. It is characterized by low heating rates, relatively long solid and vapor residence times, and sometimes by low temperature. Longer residence times result in leading secondary conversion of primary products, yielding more coke, tar, as well as thermally-stable products. Depending on the system, heating rates are about 0.1 to 2 ^{0}C per second and prevailing temperatures are around 500^{0}C [M.R. Islam et al. 2008].

b. Fast Pyrolysis

In contrast to slow pyrolysis, fast pyrolysis indicates a rapid thermal decomposition characterized by higher heating rates. This process usually requires a feedstock with small particle sizes and specially-designed devices to allow quick removal of the vapors released. Fast pyrolysis is recognized as an effective conversion route for the production of liquid fuels, chemicals and derived products with higher yield (usually around 50–60 wt. % for rubber feedstock) [Ani and Matnor, 2012].

Table 2: Types of pyrolysis with their residence time, heating rate at different temperature range [Haniu et al. 2008].

Pyrolysis type	**Residence time**	**Heating rate**	**Temp (^{o}C)**	**Major products**
Slow pyrolysis	Hours – days	Very low	300 – 500	Charcoal
Conventional pyrolysis	5 – 30 min	Medium	400 – 600	Char, liquids, syngas
	5 – 30 min	Medium	700 – 900	Char, syngas
Fast pyrolysis & (flash pyrolysis)	0.1 – 2 sec	High	400 – 650	Liquids
	< 1 sec	High	650 – 900	Liquids, syngas
	< 1 sec	Very high	1000 – 3000	Syngas

The only difference b/n flash and fast pyrolysis (more accurately defined as thermos-lysis) is heating rates and hence residence times and products derived. Heating rates are b/n 200 and 105 ^{0}C/s and the prevailing temperatures are usually higher than 500^{0}C. Due to the short vapor residence time, products are high quality, ethylene-rich gases that could subsequently be used to produce alcohols or gasoline. Notably, the production of char and tar is considerably less during this process

Table 3: Tyre pyrolysis reactors – characteristics and advantages [M.R. Islam et al. 2008].

Reactor type	**Characteristics**	**Advantages**
Vacuum Moving-Bed Process	200 kg/h pilot-scale continuous moving bed	Evaporating volatiles can be immediately removed from the reactor, which minimizes secondary reactions such as thermal cracking, re-polymerization, and re-condensation. As a result, the oil yield is dramatically increased at the expense of char and gas.
Fluidized Bed Process	120 kg/h indirectly heated fluidized bed& (High Moderate)	Research efforts have been conducted at lower temperatures (< 700ºC) in order to improve the oil yield and to reduce the energy input
Continuous Ablation Reactor	Ablation is achieved by sliding contact of the rubber particles on a hot metal surface, which resulted in a high yield of liquids because of the fast heating of the tyre. 1500−2000 kg/h commercial plant.	Pyrolytic char can be converted to activate char with steam or carbon dioxide. The activated char worked well for the removal of organics and heavy metals from aqueous solutions.
Two-Stage Moving-Bed Process.	During the first stage, the tire is depolymerized at 500°C. During the second stage, the pyrolytic volatiles are post cracked at temperatures of 750−800°C.	Oil yields of 37.0−42.2 wt %, solid yields of 41.7−45.3 wt %, and gas yields of 6.0−19.5 wt %. The contents of oils are quite high.
Continuous Rotary Kiln process	Its heat method is a Wall heating system and its heat rate is low	A rotary kiln pyrolyzer offers many advantages over other types of reactors. The residence time of solids can be easily adjusted to provide the optimum conditions of pyrolysis reaction.

2.2.2. Pyrolysis Process and Yields

i) Pyrolysis process

The waste tyre pyrolysis was carried out on an innovative pilot scale pyrolyser, developed and patented within this study, consisting of a thermo-mechanic cracking reactor designed as a twin-screw extruder with decreasing section that realizes a mixing and mechanical pressing of the material.

Tyre pieces are continuously fed inside the pyrolysis reactor and the holding time is controlled by the revolution speed of the electric motor connected to the extruder through an adaptor. The pyrolysis reactor is externally heated by two independent electrical resistances and temperature controllers are used to regulate the temperatures.

The evolved pyrolysis oil vapors and gases are separated from the solid (carbon black) by a cylindrical chamber (separator), where the temperature is maintained at about 800–900 ^{0}C by external heat supply. Then, vapor and gasses, at a temperature of roughly 900 ^{0}C, enter into a water cooled condenser to cool. The condensed liquid (TPO) will be collected in a tank and finally distillate tyre oil product for about 200 – 270 ^{0}C (Diesel Range) and >270 ^{0}C (Lubricating Oil) in distillation laboratory [William and Besler, 1995].

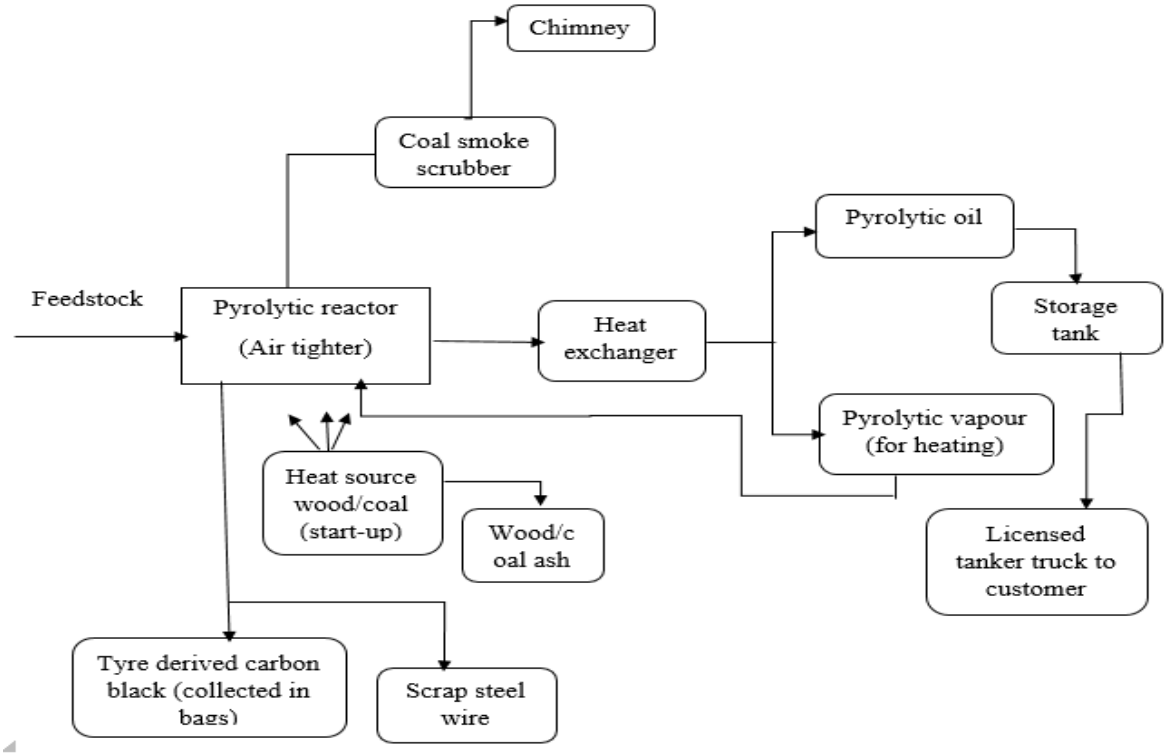


Fig. 8: Simplified waste tyre pyrolysis process flow diagram [William and Besler, 1995].

A flow diagram of tyre pyrolysis process, including the proposed thermal decomposition model, is presented in Fig. 9.

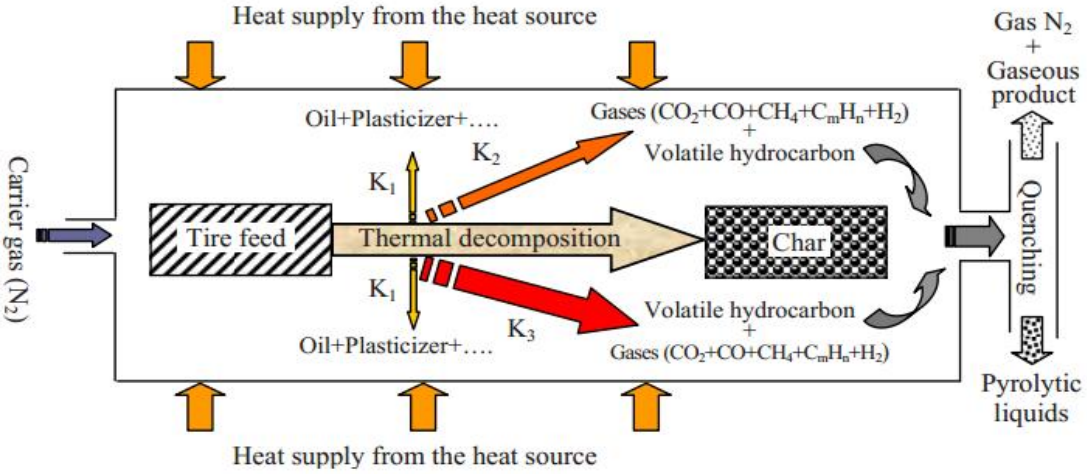


Fig. 9: Flow diagram of tyre pyrolysis process in pyrolytic [Wang et al. 2016].

The three types of arrows in the flow diagram indicate three decomposition reactions. The higher weight or colour deepness of the arrows indicates the decomposition of the corresponding tyre material in the higher temperature regions.

Thus, the global pyrolysis reaction that takes place into a reactor can be described in the following manner:

- Tyre wastes volatile hydrocarbon + gases + solid residues
- Tyre wastes, fed into the pyrolysis reactor undergo a thermal cracking, by cleaving itself into volatile hydrocarbon, gases and solid residue.
- Volatile hydrocarbon can be cooled and condensed into a liquid fraction
- Gaseous fraction remains uncondensed during quenching.
- Solid residues wait in the reactor chamber for their removal.

Normally, the process provides:

- Solid residues containing steel cord and char, containing fixed carbon and ashes (metals, oxides and inert matter).
- A liquid fraction , composed of water, tar and oils (organic compounds);

- A gaseous fraction, essentially composed of CH_4, and higher hydrocarbons C_mH_n, H_2, CO_2, CO etc.

a) **Tyre Pyrolysis Solid**

The solid fraction obtained is a carbonaceous material with particle size smaller than 100 μm and an average composition of 82.6 wt% C, 1.0% H, 0.1% N, 2.5% S, 1.8% Si, 4.3% Zn And other elements (Mg, Ca Al, Na & K) in traces (<0.1%). S, Si and Zn derive from the Sulphur used in the vulcanization process and from the inorganic fillers of the original tyres, respectively. The solid residue from tyre pyrolysis may have potential applications such as solid combustible, carbon black for rubber manufacture, filler in road bitumen or active carbon after physical or chemical activation [Shah et al. 2007].

b) **Tyre Pyrolysis Liquid**

Pyrolysis oils obtained using a crushed tyre flow rate of 10 kg/h were mixed and homogenized prior to be analyzed. The pyrolytic oil appeared dark brown with a strong acrid smell. Density, viscosity, calorific value and flash point of TPO are comparable to those of DF, but Sulphur content is significantly higher precluding TPO use in road vehicles. Another important parameter that has to be carefully considered when an unconventional fuel is used inside a compression ignited engine is the cetane number (CN). When the traditional CN cannot be directly measured, as in the present case, it is possible to have a good estimation of it calculating the cetane index (CI) [Jan et al. 2007].

c) **Tyre Pyrolysis Gas**

The pyrolysis gases were collected in cylinders during the experiments and analyzed by gas chromatography using a Thermo Quest Trace (TQT) equipped with a flame ionization detector (FID). The carbon oxide components (COx) are mostly derived from the oxygenated organic compounds in tyres, such as stearic acid and extender oils. H2S is a product of the Sulfur links vulcanized rubber structure decomposition and its concentration is low. C4 and >C4gases are the most predominant products and these result from the de-polymerization of styrene-butadiene-rubber (SBR), usually the main constituent of automotive tyres. Table below shows the gaseous constituents produced during the pyrolysis of tyres. The gaseous product mixture is made of shorter aliphatic chains than SBR due to rubber cracking and subsequent reactions to form lighter gases. The pyrolysis derived gas has a calorific value of approximately 30-40MJ N/m-3 and can be sufficient to provide the energy required for a small scale process plant [Mabood et al. 2007].

Table 4: Pyrolysis gas constituent [Shah et al. 2007].

Pyrolysis Gas Constituents			
Component	**Chemical formulas**	**Component**	**Chemical formulas**
Carbon monoxide	CO	Butane	C_4H_{10}
Carbon dioxide	CO_2	Butene	C_4H_8
Hydrogen sulphide	H_2S	Butadiene	C_4H_6
Methane	CH_4	Pentane	C_5H_{12}
Ethane	C_2H_6	Pantene	C_5H_{10}
Propane	C_3H_8	Hexane	C_5H_{14}
Propene	C_2H_6	Hexene	C_6H_{12}

ii) Pyrolysis Yields

The pyrolysis process yields a gaseous fraction of mainly non-condensable gases, a solid fraction mainly composed of carbon, metal and others inert material as well as an oily fraction mainly composed of organic substances condensable at ambient temperature and pressure [Haydary et al. 2012].

- Typical product yield and utilization is discussed here.

a) Non-condensable gases (10 to 12%)

Waste tyre pyrolysis is a complex reaction that produces light hydrocarbons which do not condense at room temperature and pressure called the non-condensable gas. The non-condensable gas comprises mainly CO_2, CO, H_2, CH_4, C_2H_6, C_3H_6,C_3H_8, and C_4H_6, with 1% sulfur content and lower concentrations of other hydrocarbon gases [Haydary et al. 2012; Williams, 2013].

b) Tyre char (30 to 35%)

The residue, excluding the steel wires, produced by waste tyre pyrolysis is called tyre char, which contains 15% inorganic Ash (mostly ZnO), 3-5% sulfur, carbon black and high boiling points tar. The existence of carbon black is due to the fact that carbon black is one of the tyre components [Haydary et al. 2012; Williams, 2013].

The char activation chemistry can represented by the following two reactions:

i. CO2 activation:

$$CO_2 + C \rightleftharpoons 2CO$$

(The Boudouard reaction)

ii. Steam activation:

$$H_2O + C \rightleftharpoons CO + H_2$$

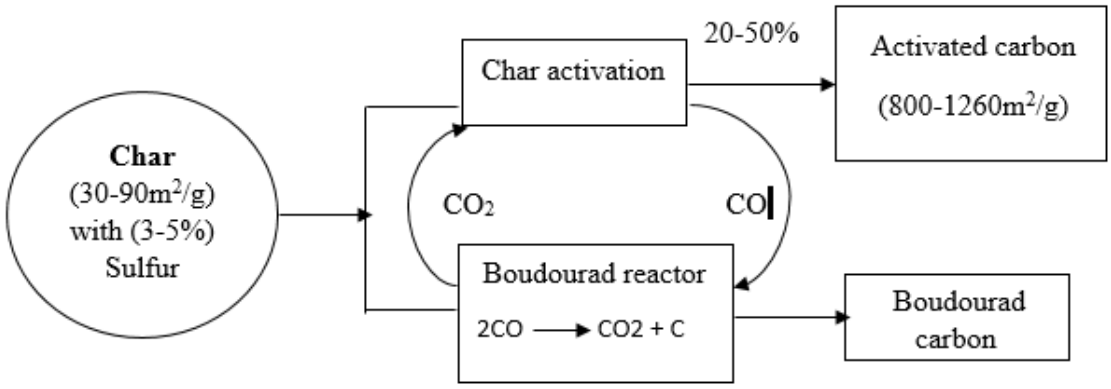


Fig. 10: Upgrading process of carbon from char and its yield [Haydary et al. 2012].

c) Steel wires (10 to 15%)

Waste tyre pyrolysis can also generate scrap steel wire due to the fact that steel wires can be used as reinforcement agent for tyre [Haydary et al. 2012; Williams, 2013].

d) Tyre pyrolysis oil (40 to 45%)

The oil products are highly aromatics with low sulfur (0.3-1%) and 300-400 g/mol BTX. The main oil product produced by pyrolysis technology is the fuel oil that is widely used for industrial and commercial purposes [Haydary et al. 2012; Williams, 2013].

2.2.3. Tyre Pyrolysis Oil (TPO)

Tyre pyrolysis oil plant has been established around the world in order to produce the substitute liquid fuel for heating purpose as found that the tire pyrolysis oil have a high gross calorific value (GCV) of around 41-44 MJ/kg. Waste tyre is needed to be shredded before process. The desulphurization is required in the pyrolysis system to eliminate the sulfur [Tudu et al. 2016].

TPO could be used in large stationary engines, for example for the combined production of electricity and heat, where systems of Sulphur removal from the exhaust gases can be provided so as to comply with the emission limits. In addition, it can be assumed the use of this pyrolysis oil in medium/low speed engines for marine propulsion, commonly used in large vessels for transporting goods or passengers, which are characterized by a rotation speed ranging from 50 to 600 rpm with less requirements both from the point of view of combustion and of the fuel injection system (marine engines can accept fuels with a minimum CI = 35 and with Sulfur content up to 2% wt. Thus these engines are better suited to the use of fuels, such as the pyrolytic oil produced in this study, with low cetane number and high Sulphur content. However, it is worth considering TPO employ in small engines, e.g. for small electric generators or for agricultural applications, since it may well lead to a widespread energetic utilization of scrap tires [Cunliffe and Williams, 1998].

2.2.4. Characteristic of Pyrolysis Oil

Pyrolysis is a complex series of chemical and thermal reactions to decompose or depolymerize organic material under oxygen-free conditions. The products of pyrolysis include oils, gases and char. The pyrolysis oil products in this research are from tire and tyre plastic which are dissimilar in physical properties and chemical properties. The appearance of the tire pyrolysis oil is thick-liquid and dark color oil [Akyildiz et al. 2012].

2.2.5. Modification of Tyre Pyrolysis Oil (TPO)

The modification of the crude TPO involves three stages,

1) removal of moisture
2) Desulphurization
3) Distillation process.

I. Removal of moisture

Initially crude TPO will be heated up to 100 ^{o}C, in a cylindrical vessel for a particular period to remove the moisture, before subjecting it to any further chemical treatment [Murugan et al. 2008].

II. Desulfurization

The moisture free crude TPO contains impurities, carbon particles and Sulphur particle. A known volume of concentric hydro-sulfuric acid (8%) will be mixed with the crude TPO and stirred well. The moisture-free crude TPO contains impurities, carbon particles, and sulfur

particles. The mixture is kept for about 40 hours. After 40 hours, the mixture is found to be in two layers. The top layer is a thin mixture and the bottom layer is thick sludge. The top layer is taken for atmospheric distillation and the sludge is removed and disposed off. In the desulfurization process, the efficiency of sulfur removal is 61.6% [Aydin and Ilkilic, 2012; Chen et al.2010].

III. Distillation Process

Distillation is a commonly used method for purifying liquids and separating mixtures of liquids into their individual components. The distillation process is shown in Figure below.

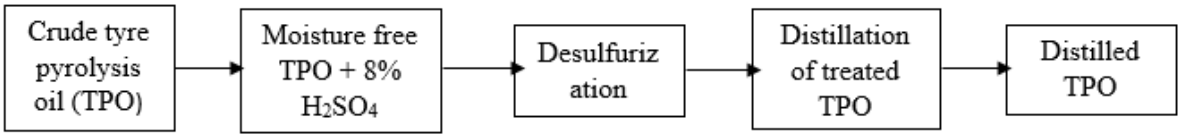


Fig. 11: Distillation of tyre pyrolysis oil [Ramaswamy et al. 2008].

Atmospheric distillation process is carried out to separate the lighter and heavier fraction of hydrocarbon oil. A known sample of chemically treated crude TPO is taken for vacuum distillation process. Vacuum distillation process will be carried out to separate the lighter and heavier fraction of hydrocarbon oil. The sample is externally heated in a closed chamber by electric heater of 1.5 kW. The vapor leaving the chamber is condensed in a water condenser and the distilled tire pyrolysis oil (DTPO) is collected separately. Non condensable volatile vapors are left to the atmosphere. The distillation is carried out at 150–370°C because the maximum amount of DTPO is obtained within this range. Nitrogen gas is supplied to carry out producer gas from the reactor to the condenser and also create inert environment to the reactor. 80% of TPO is distilled in the distillation whereas 5% of TPO is left out as pyro gas and 15% is found as sludge. The DTPO has irritating odor like acid smell. The odor can be reduced with the help of adding some masking agents or odor removal agents [Ramaswamy et al. 2008].

2.2.6. Factors Affecting Tyre Pyrolysis Process

The composition of the pyrolysis products is influenced by the process operating conditions such as,

- Tyre shred size (feed size),
- pyrolysis temperature,
- Residence time of the pyrolysis products,
- Pyrolysis pressure,

- Heating rate,
- Carrier gas Flow Rate/Volatiles Residence Time
- Catalyst used.

♦ **Feed Size/Tyre sherd size**

Smaller feed size particles provide more reaction surface, giving high heating rate and rapid decomposition of rubber. The oil product vapors comparatively get enough time for secondary reactions in the reactor and this consequently increases gas yield and reduces liquid and char yields. On the other hand, the heating rate in whole tyre feed is low due to its lower thermal conductivity, in addition heat can flow only to a certain depth in the available pyrolysis time compared to almost complete thermal decomposition of the smaller pieces. Thus, the rubber core of the larger pieces becomes carbonized and/or cannot be decomposed completely resulting in increased char yield and decreased liquid and gas yield [Haydary et al. 2012].

♦ **Temperature**

The increase in gas yield with a corresponding reduction in liquid yield with increase in temperature is due to vapor decomposing into permanent gases, and secondary re-polymerization as well as carbonization reactions of oil hydrocarbons into char. It is also a result of char loss and thermal cracking. Thus, gas yields dominate at higher temperature [Haydary et al. 2012].

♦ **Pyrolysis time/Residence time**

Pyrolysis time is related to particle size: in general, larger particles require longer residence times to achieve the same degree of conversion. Longer residence times require a larger reactor, with larger capital costs. Pyrolysis time is also linked to heating rate, with lower heating rates requiring longer pyrolysis times. An increase in vapor residence time decreases liquid and char yields while the gas yield increases slightly. This is due to the decomposition of some oil vapor into secondary permanent gases. Primary vapors are first produced from tyre pyrolysis at optimum temperature, the primary oil vapors then degrade into secondary gases. For instance: oil Vapors→ heavy hydrocarbons + light hydrocarbons (CH_4 + C_2H_4 + C_3H_6 +……) + (CO + CO_2 + H_2) leading to less oils and more gaseous products. In addition, longer contact time of the volatiles and char leads to another parallel secondary pyrolysis reaction: C + CO_2 → 2CO which reduces the char yield [Haydary et al. 2012].

- **Pressure**

Increasing pyrolytic pressure has been found to increase oil viscosity. On the other hand, reduced pressure (often associated with vacuum pyrolysis), has been found to reduce secondary reactions in the gas phase, by reducing volatiles residence time; this would tend to increase oil yield. Also, reducing secondary reactions can reduce gas deposition onto the solid char surface, which can make the char more valuable as an activated carbon adsorbent, with higher surface area and increased reactivity. Decreasing process pressure may also decrease process temperature (PV = nRT, according to the ideal gas law); decreasing process temperature decreases energy demand [Haydary et al. 2012].

- **Heating Rate**

Increasing the heating rate increases the degradation rate, and also affects the temperature at which maximum volatilization starts and stops. Higher heating rates lead to higher temperatures, which can lead to more secondary reactions, which can produce more gas-phase products. The nature of the secondary reactions can impact the composition of the gas as well as the liquid. Heating rate, as well as temperature and particle size, can produce different impacts depending on values of other parameters. Heating rate also impacts the time to complete pyrolysis and energy required: lower heating rates necessitate longer residence times, but require less energy. Heating rate is linked to reactor type, with certain reactor types producing higher heating rates [Haydary et al. 2012].

- **Carrier gas Flow Rate/Volatiles Residence Time**

An increase in carrier gas flow rate carries the gaseous products away more quickly, decreasing the volatile product's residence time. A longer volatile residence time means that secondary reactions are more likely to occur, which can decrease oil yield if liquid phase compounds convert to gas phase. Thus, increasing carrier gas flow rate has been found to increase oil yield [Haydary et al. 2012].

- **Catalyst**

Catalysts can be used to improve pyrolysis rate, oil quality, oil yield, and yields of compounds such as aromatics for chemical production [Haydary et al. 2012].

2.3. Waste Tyre Recycling Methods

To convert the waste tyre into a valuable product, it must first be reduced in size and then recycled. The recycling process begins first by shredding tyres into small manageable chips, which are then cooled to cryogenic temperatures, causing the pieces to become brittle. These

brittle pieces are then pulverized into a material that must be screened to remove large chunks of rubber or polymer. Finally, the remaining fibre and magnetic material are separated from the pulverized material using a magnetic separator and a vibration separator. And then the wastage tyre are fed into the reactor vessel and heated under controlled conditions of temperature and pressure at oxygen free environment to melt but not to burn. After it has melted, it will start to boil and evaporate [Scherirs and Kaminsky, 2006; Lopez et al. 2011].

The process will being about molecular restructuring of the rubber under the pyrolysis process as the result;

- Furnace oil in gaseous form is produced along with other gases.
- These vaporized gases are passed through heat exchanges, where in the furnace oil is condensed into liquid form and some of the vapours with shorter hydrocarbon lengths will remains as a gas (similar to propane).
- During the process, carbon black and steel are also generated.
- The heat exchanges uses coolant water as a condensing medium and this water is re-circulated through process.

This form of recycling is environmentally friendly, and allows a valuable resource to be used again and again.

There is a potential for using waste tyre rubber to make activated-carbon adsorbents for air-quality control applications. Such an approach provides a recycling path for waste tyres and the production of new adsorbents from a low-cost waste material. Also, recycled rubber from tyre is used as a component of various products commonly known as "tyre derived products"[Lopez et al. 2011].

- The basic process of tyre recycling methods in pyrolysis plant are;

A. Chemical De-polymerization

Chemical de-polymerization, or chemo lysis, involves the reaction of the used polymer with chemical reagents for the production of its starting monomers. The most predominant compounds were 1-butene, isoprene (2-methyl 1, 3 butadiene) and cis-pentene. 1-butene and isoprene derive from the de-polymerization of butyl rubber and isoprene rubber, respectively.

B. Gasification

Gasification is the partial thermal degradation of a substance with insufficient oxygen to oxidize the fuel completely. The partial oxidation of organic matter at high temperatures (typically between 800-1500ºC) under mild oxidizing conditions (usually steam, carbon

dioxide or Sub stoichiometric oxygen) for the production of synthesis gas (syngas). This gas consisting primarily of carbon monoxide and hydrogen, has application in the synthesis of chemicals like methanol and ammonia, and can be used to produce synthetic diesel or may be combusted directly as a fuel.

- Carbonaceous material + heat → char + liquid organic species + gas phase organic species (**pyrolysis chemical reaction**)
- Char + gasifying agent +heat → gas phase organic species + ash (**gasification chemical reaction).**During oxidizing agent, Air/oxygen/steam is used and/or to act as a carrier gas to remove the reaction products from reaction.

  - Row material decomposition and its solid-gas reactions

$$C_XH_Y \Leftrightarrow xC + \frac{Y}{2}H_2 \quad \text{(1)}$$

  - Reactions with oxygen

$$C + \frac{1}{2}O_2 \Leftrightarrow CO \quad \text{(2)}$$

$$CO + \frac{1}{2}O_2 \Leftrightarrow CO_2 \quad \text{(3)}$$

$$H_2 + \frac{1}{2}O_2 \Leftrightarrow H_2O \quad \text{(4)}$$

$$C_XH_Y + \left(X + \frac{Y}{4}\right)O_2 \Leftrightarrow xCO_2 + \frac{Y}{2}H_2O \quad \text{(5)}$$

$$C_XH_Y + \left(\frac{X}{2} + \frac{Y}{4}\right)O_2 \Leftrightarrow xCO + \frac{Y}{2}H_2O \quad \text{(6)}$$

  - Reactions with water

$$C + H_2O \Leftrightarrow CO + H_2 \quad \text{(7)}$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \quad \text{(8)}$$

$$C_XH_Y + xH_2O \Leftrightarrow xCO + (\frac{Y}{2} + X)H_2 \quad \text{(9)}$$

  - Reactions with CO_2

$$C + CO_2 \Leftrightarrow 2CO \quad \text{(10)}$$

$$C_XH_Y + xCO_2 \Leftrightarrow 2xCO + \frac{Y}{2}H_2 \quad \textit{(11)}$$

  - Methanation reaction (gas-gas reactions)

$$CO + 3H_2 \Leftrightarrow CH_4 + H_2O \quad \text{...} (12)$$

$$CO_2 + 4H_2 \Leftrightarrow CH_4 + 2H_2O \quad \text{...} (13)$$

C. Thermal Cracking

Thermal cracking, or pyrolysis, involves the degradation of the polymeric materials by heating in the absence of oxygen. The process is usually conducted at temperatures between 800- 900ºC and results in the formation of a carbonized char and a volatile fraction that may be separated into condensable hydrocarbon oil and a non-condensable high calorific value gas. The proportion of each fraction and their precise composition depends primarily on the nature of the tyre waste but also on process conditions.

D. Catalytic Conversions

Catalytic conversion of tyre wastes implies several advantages over conventional pyrolytic methods. The most evident relates to the lower degradation temperatures at which degradation reaction takes place, which results in lower energy consumptions and higher conversion rates.

E. Hydrogenation

Hydrogenation of plastics is a potential alternative for breaking down the polymer chain. Compared to treatments in the absence of hydrogen, hydrogenation leads to the formation of highly saturated products, avoiding the presence of olefins in the liquid fractions, which favors their use as fuels without further treatments. Moreover, hydrogenation promotes the removal of hetero atoms, such as chlorine (Cl), nitrogen (N) and Sulphur (S), in the form of volatile compounds. However, hydrogenation suffers several drawbacks, mainly due to the cost of hydrogen and the need to operate under high pressure.

2.4. Economic Value to the Community

The technology helps to save land filled tyre waste by utilizing the recycling process to generate in to valuable resources. Waste or Scrap tyres are made out of a material which can have no economic end use. This means that tyres which are no longer suitable for use on vehicles due to wear or damage can be recycled to serve a new economic purpose (rubber asphalt and concrete, fuel alternatives, carbon sources, etc. The developed technology will prove to be beneficial to the country for the purpose of catering increasing demand of fuel / energy and will save millions of foreign exchanges. Increased utilization of a fuel obtained from waste tyre results in significant microeconomic benefits to both the urban and rural sectors, and the balance of trade.

- Production of fuel from waste tyre can help close the trade gap by substituting imported petroleum.
- To reduce petroleum import bills and secure oil fuel supply.

2.5. Diesel Fuel

Diesel fuel in general is any liquid fuel used in diesel engines, whose fuel ignition takes place, without any spark, as a result of compression of the inlet air mixture and then injection of fuel. Diesel engines have found broad use as a result of higher thermodynamic efficiency and thus fuel efficiency. The average chemical formula for common diesel fuel is $C_{12}H_{24}$, ranging approximately from $C_{10}H_{20}$ to $C_{15}H_{28}$.Conventional diesel fuels vaporize at temperatures between 149 °C and 371 °C [Alferd and Rudolf Diesel, 1913].

Diesel fuel is heavier than gasoline because it is obtained from the residue of the crude oil after the more volatile fuels have been removed. As with gasoline, the efficiency of diesel fuel varies with the type of engine in which it is used. By distillation, cracking, and blending of several oils, a suitable diesel fuel can be obtained for all engine operating conditions. Using a poor or improper grade of fuel can cause hard starting, incomplete combustion, a smoky exhaust, and engine knocks. The high injection pressure need in the diesel fuel system result from close tolerances in the pumps and injectors. These tolerances make it necessary for the diesel fuel to have sufficient lubrication qualities to prevent rapid wear or damage. It must also be clean, mix rapidly with the air, and burn smoothly to produce an even thrust on the piston during combustion [Rudolf Diesel, 1913].

Diesel fuel is graded and designated by the American Society for Testing and Materials (ASTM), while its specific gravity and high and low heat values are listed by the American Petroleum Institute (API). Each individual oil refiner and supplier attempts to produce diesel fuels that comply as closely as possible with ASTM and API specifications. Because of different crude oil supplies, the diesel fuel may be on either the high or low end of the prescribed heat scale in BTU per pound or per gallon. Because of the deterioration of diesel fuel, only two grades of fuel are considered acceptable for use in high-speed heavy-duty vehicles. These are the No. 1D or No. 2D fuel oil classification. Grade No. 1D comprises the class of volatile fuel oils from kerosene to the intermediate distillates [Alferd, 1913].

Fuels within this classification are applicable for use in high-speed engines in service involving frequent and relatively wide variations in loads and speeds. In cold weather conditions, No. 1D fuel allows the engine to start easily. In summary, for heavy-duty high-

speed diesel vehicles operating in continued cold-weather conditions, No. 1D fuel provides better operation than the heavier No. 2D. Grade No. 2D includes the class of distillate oils of lower volatility. They are applicable for use in high-speed engines in service involving relatively high loads and speeds. This fuel is used more by truck fleets due to its greater heat value per gallon, particularly in warm to moderate climates. Even though No. 1D fuel has better properties for cold weather operations, many still use No. 2D in the winter, using fuel heater/water separators to provide suitable starting, as well as fuel additive conditioners, which are added directly into the fuel tank. [Alferd and Rudolf Diesel, 1913].

2.6. Important Properties of Diesel Fuel

The fuel properties of diesels are characterized by determining their viscosity, density, cetane number, volatility, cloud points, distillation range, flash point, ash content, sulfur content, carbon residue, calorific value, acid value, copper corrosion, and higher heating value.
The major functional properties of diesel fuel and how important are listed below.

Table 5: Major functional properties of diesel fuel and how they are important [Rudolf Diesel, 1913]

Diesel fuel properties	Why is it essential? b/c
Heat value (BTU/gal)	Affects power and economy
Viscosity	Affects atomization
Cetane number	Affects cold starting, smoke, combustion roughness
Sulfur content	Affects wear and deposit
Cloud and Pour point	Affects low temperature handling
Cleanliness and Stability	Affects fuel filter life and injector life

2.6.1. Heating Value

One of the major constitutes of a diesel fuel oil is hydrogen, with water being the byproduct of combustion when the hydrogen is burned. This water may remain in the vapor form in the hot combustion gases or, if the gases are cooled, then the water vapor will be to a liquid state, giving up its latent heat of vaporization. The value of a fuel is determined in a calorimeter. The product of combustion are cooled to the original temperature, the water vapor is condensed, the total heat released is known as the gross or high heat value (HHV) of the fuel (BTU per pound for liquid fuel or BTU per cubic feet for gaseous fuel).

2.6.2. Cetane Number

Cetane number is a measure of the ignition quality of the fuel, fuel oil's volatility; the higher the rating, the easier the engine will start and the smoother the combustion process will be within the ratings specified by the engine manufacturer. Current 1D and 2D diesel fuels have a cetane rating between 40 and 50. Cetane rating differs from the octane rating used in gasoline in that the higher the number of gasoline on the octane scale, the greater the fuel resistance to self-ignition, which is a desirable property in gasoline engines with a high compression ratio. Using a low octane fuel will cause premature ignition in high compression engines. However, the higher the cetane rating, the easier the fuel will ignite once injected into the diesel combustion chamber. If the cetane number is too low, you will have difficulty in starting. This can be accompanied by engine knock and puffs of white smoke during warm-up in cold weather. High altitudes and low temperatures require the use of diesel fuel with an increased cetane number. Low temperature starting is enhanced by high cetane fuel oil in the proportion of 1.5°F lower starting temperature for each cetane number increase.

2.6.3. Volatility

Fuel volatility requirements depend on the same factors as cetane number. The more volatile fuels are best for engines where rapidly changing loads and speeds are encountered. Low volatile fuels tend to give better fuel economy where their characteristics are needed for complete combustion, and will produce less smoke, odor, deposits, crankcase dilution, and engine wear.

The volatility of a fuel is established by a distillation test where a given volume of fuel is placed into a container that is heated gradually. The readiness with which a liquid changes to a vapor is known as the volatility of the liquid. The 90 percent distillation temperature measures volatility of diesel fuel. This is the temperature at which 90 percent of a sample of the fuel has been distilled off. The lower the distillation temperature, the higher the volatility of the fuel. In small diesel engines higher fuel volatility is needed than in larger engines in order to obtain low fuel consumption, low exhaust temperature, and minimum exhaust smoke.

2.6.4. Distillation Range

The distillation range of a fuel affects its performance and safety. It is an important criterion for an engines start and warm up. It is also needed in the estimation of the cetane index. The distillation range of the liquid product is determined by a test method (ASTM D 86) that

covers the determination of the boiling range distribution of liquid fuels [Rudolf Diesel, 1913].

$$C_c = 0.00012\ (760\text{-}p)\ (273 + t_c) \quad \ldots\ldots (14)$$

Where, t_c = The observed temperature reading, ^0C

C_c = Corrections to be added algebraically to the observed temperature readings.

P = Barometric pressure, prevailing at the time and location of the test, mmHg.

Hence, corrected temperature

$$^0C = t_c + C_c \quad \ldots\ldots (15)$$

2.6.5. Viscosity

The viscosity is a measure of the resistance to flow of the fuel, and it will decrease as the fuel oil temperature increases. What this means is that a fluid with a high viscosity is heavier than a fluid with low viscosity. A high viscosity fuel may cause extreme pressures in the injection systems and will cause reduced atomization and vaporization of the fuel spray. The viscosity of diesel fuel must be low enough for it to flow freely at its lowest operational temperature, yet high enough to provide lubrication to the moving parts of the finely machined injectors. The fuel must also be sufficiently viscous so that leakage at the pump plungers and dribbling at the injectors will not occur. Viscosity also will determine the size of the fuel droplets, which in turn govern the atomization and penetration qualities of the fuel injector spray. Recommended fuel oil viscosity for high-speed diesel engines is generally in the region of 39 SSU (Seconds Saybolt Universal), which is derived from using a Say bolt Viscometer to measure the time it takes for a quantity of fuel to flow through a restricted hole in a tube. A viscosity rating provides good penetration into the combustion chamber, atomization of fuel, and suitable lubrication.

There are two different ways of measuring viscosity

- Dynamic viscosity
- Kinematic viscosity

$$\text{Dynamic viscosity} = \frac{shear\ stress}{Rate\ of\ shear} \quad \ldots\ldots [16]$$

The unit for dynamic viscosity is milli pascal seconds (mpa. s) or centipoises

$$\text{Kinematics viscosity} = \frac{Dynamic\ viscosity}{Density} \quad \ldots\ldots [17]$$

The unit for kinematics viscosity is mm^2/s or centistokes (cSt).

The other way of calculating kinematic viscosity is product of the time (t) in seconds and the calibration constant (k) of the viscometer tube.

Kinematics viscosity = K * t …… [18]

Where, K = Calibration constant for the viscometer in (mm^2/s).

T = Time in (s)

2.6.6. Sulfur Content

Sulfur has a definite effect on the wear of the internal components of the engine, such as the piston ring, pistons, valves, and cylinder liners. In addition, a high sulfur content fuel requires that the engine oil and filter be changed more often because the corrosive effects of hydrogen sulfide in the fuel and the sulfur dioxide or sulfur trioxide that is formed during the combustion process combine with water vapor to form acids. High additive lubricating oils are desired when high sulfur fuels are used. Refer to the engine manufacturer's specifications for the correct lube oil when using high sulfur fuel. Sulfur content can be established only by chemical analysis of the fuel. Fuel sulfur content above 0.4% is considered as medium or high, and anything below 0.4% is low. No. 2D contains between 0.2 and 0.5% sulfur, whereas No. 1D contains less than 0.1%. Sulfur content has a direct bearing on the life expectancy of the engine and its components. Active sulfur in diesel fuel will attack and corrode injection system components and contribute to combustion chamber and injection system deposits.

2.6.7. Flash point

This condition has nothing at all to do with the combustion phase or performance of the fuel in the engine but is rather a measure of the temperature at which the fuel oil vapors will flash when in the presence of an open flame. Safety in handling storage is the only warranting consideration for flash point.

2.6.8. Cloud point

Cloud point is the temperature at which wax crystals in the fuel (paraffin base) begin to settle out with the result that the fuel filter becomes clogged. This condition exists when cold temperatures are encountered and is the reason that a thermostatically controlled fuel heater is required on vehicles operating in cold weather environments. Failure to use a fuel heater will prevent fuel from flowing through the filter and the engine will not run. Cloud point generally occur 9-14°F above the pour point.

2.6.9. Pour point

Pour point of a fuel determines the lowest temperature at which the fuel can be pumped through the fuel system. The pour point is expressed as 5°F above the level at which the oil becomes a solid or refuses to flow.

Pour point is generally about 10^0F lower than the cloud point, although flow improvers can result in satisfactory fuel flow at about 9^0C colder temperature than is possible with untreated fuel.

2.6.10. Calorific Value

Calorific value of a fuel is the thermal energy released per unit quantity of fuel when the fuel is burnt completely and the products of combustion are cooled back to the initial temperature of the combustible mixture. It measures the energy content in a fuel. The calorific value of waste oils was measured in a bomb calorimeter according to ASTMD240 standard method.

2.6.11. Cleanliness and Stability

Cleanliness is an important characteristic of diesel fuel. Fuel should not contain more than a trace of foreign substances; otherwise, fuel pump and injector difficulties will develop, leading to poor performance or seizure. Because it is heavier and more viscous, diesel fuel will hold dirt particles in suspension for a longer period than gasoline. Moisture in the fuel can also damage or cause seizure of injector parts when corrosion occurs. Fuel stability is its capacity to resist chemical change caused by oxidation and heat. Good oxidation stability means that the fuel can be stored for extended periods of time without the formation of gum or sludge. Good thermal stability prevents the formation of carbon in hot parts such as fuel injectors or turbine nozzles. Carbon deposits disrupt the spray patterns and cause inefficient combustion.

2.6.12. Corrosion

This is the tendency of the fuel oil to react with copper, brass, or bronze parts of the fuel system. This specification does not indicate the corrosion of parts of the engine, which may occur from the use of high sulfur fuels with low engine temperature. Corrosion is determined by immersing a strip of polished copper in the fuel for a period of three hours at 212 ^{0}F; the results are interpreted as (1) slight tarnish (2) moderate (3) dark tarnish or (4) corrosion.

2.6.13. Specific gravity (sp.gr)

This is the ratio of the weight of the fuel oil to that of an equal volume of water, which weighs 10 pounds per imperial gallon; therefore water is given as a specific gravity number

of 1. Specific gravity is commonly designated as ‘‘sp.gr 60/60 ^{0}F’’ indicating that both the fuel oil and the water are weighed and measured at a temperature of 60^{0}F.on the other hand, the API gravity of a liquid is measured with special hydrometer, the float of which gives a reading at the surface of the in degrees API. A temperature correction must be applied to the observed reading to obtain the degrees in API at 60 ^{0}F (standard temperature).

2.6.14. API

The API (American Petroleum Institute) gravity of a fuel oil has no direct effect on engine performance, but it does indicate the fuel oil’s viscosity, its distillation characteristics (temperature at which the fuel vaporizes) and the heating value of the fuel in BTUS’s. Heavier distillates of fuel oil contain more BTU’s per gallon than the lighter distillate fuel oils; therefore, all things being equal the engine can produce more horse power per gallon of fuel used. However, these heavier distillates generally create more exhaust smoke and door. The fuel economy with the heavier distillates may not be as good as in some cases as with that of the lighter fuel oils.

$$\text{API gravity} = \frac{141}{sp.gr\frac{60}{60}0F} - 131.5 \quad \text{[19]}$$

2.7. Typical Properties of TPO, DTPO and Diesel Fuels

Tyre Pyrolysis Oil (TPO) contains higher viscosity and sulfur content compare to diesel fuel and with this study came out that diesel fuel can be combined with Distill Tyre Pyrolysis Oil (DTPO).Cetane number of TPO is about 42 that are lower than cetane number of diesel fuel. By this value, theoretically the ignition delay for TPO is longer than diesel fuel and this can cause knocking effect for TPO is more than diesel fuel. It also might come that there are lots of power loss due to the knocking effect [Murugan et al. 2008].

Viscosity of Tyre Pyrolysis Oil (TPO) is 6.3Cs@40°C that is higher that viscosity of diesel fuel. When we compare both viscosity values, the value of diesel fuel can be accepted because it is not too low or too high. We know that when there is too high of viscosity for fuel, it can increase gear train, cam and other wear on fuel pump because of higher injection pressure. It also contributes for knocking effect of the engine.The flash point of Tyre Pyrolysis Oil (TPO) is 32°C which is lower compare to the diesel fuel that is 42°C. This is good sign because lower the flash point means easily the fuel can be combust [Kumaravel et al. 2016; Marthenz et al. 2014].

Due to its high viscosity and high sulfur content of pyrolysis oil than, its direct application as a fuel in diesel engines is not recommended, however when it was distilled at elevated temperature and blended with diesel fuel it can be used as alternative fuel.

2.8. Engine Performance Analysis

Engine performance indicates the effects of a fuel in the engine. It shows the trend and possibility of using pyrolysis oil to replace diesel oil without any engine modification. It is necessary to determine break torque (T), engine break power (P), break specific fuel consumption (bsfc), and break thermal efficiency (η_{th}). These several parameters can be obtained by measuring air and fuel consumption, torque and speed of the engine, and heating value of the oil. The performance parameters can be calculated by equations as followed [Wamankar and Murgan, 2015].

2.8.1. Break Torque

Brake torque is normally measured with a dynamometer – engine is mounted on a test bed and the shaft is connected to the dynamometer rotor. The rotor is coupled electromagnetically, hydraulically or by mechanical friction to a stator, which is supported in low friction bearings. Torque exerted on the stator with the rotor turning is measured by balancing the stator with weights, springs or pneumatic means. Torque is an indicator of the function of break torque calculated by the moment of engine arm connected to weight scale as:

$$T=Fd \quad \text{(20)}$$

Where *T* is break torque in Nm, *F* is force of engine arm applied to the load in N, and *d* is the distance of engine arm from center of the rotor to the load.

2.8.2. Engine Break Power

Engine break power (*P*) is delivered by engine and absorbed load. It is the product of torque and angular engine speed where *P* is engine break power in kW;*N* is angular speed of the engine in rpm as:

$$p = \frac{2\pi NT}{60\times1000} \quad \text{(21)}$$

The performance of the engine is highly dependent on engine design and operating parameters. The importance of the parameters to engine performance becomes evident when power and torque are expressed in terms of these parameters.

2.8.3. Break Specific Fuel Consumption

Break specific fuel consumption (bsfc) is the comparison of engine to show the efficiency of the engine against with fuel consumption of the engine in g/kW-hr where $\dot{m}_f$ is the fuel consumption rate in g/hr as:

$$BSFC = \frac{\text{Fuel flow }(\frac{\text{kg}}{\text{h}})}{\text{Brake Power (KW)}}$$

$$\text{bsfc} = \frac{\dot{\text{m}}_\text{f}}{\text{P}} \quad \text{(22)}$$

The fuel energy supplied which can be released in the combustion is given by the mass of the fuel supplied to the engine per cycle times the heating value of the fuel.

$$\eta_f = \frac{1}{\text{sfc}*Q_{HV}} \quad \text{(23)}$$

Where, η_f = Fuel conversion efficiency

Q_{HV} = Fuel heating value

In engine tests, the fuel consumption can be measured in different manner. One method is measuring the mass of the fuel tank before and after the engine test has been commenced. The difference of the two masses is the total mass of the fuel consumed during the test period in this measurement test duration will recorded and the difference will divide to the test duration to obtain fuel consumption rate on the basis of mass. The second approach is to measure fuel flow rate by using fuel flow meter. The meter is connected in fuel line between the fuel tank and fuel injection unit and continuously monitors the fuel flow rate at any time for various engine load and operating conditions. This measurement technique is more accurate and enables one to measure the fuel consumed for specific output at any given time. The third approach is mathematically approximate estimation of the injection rate through the injection nozzle. If the pressure upstream of the injector nozzle can b estimated or measured, and assuming the flow through each nozzle is quasi steady, impossible and one dimensional, the mass flow rate of fuel injected through the nozzle can approximated by the following equation.

$$\dot{\text{m}}_f = C_D A_n \sqrt{2\rho_f \Delta P} \quad \text{(24)}$$

Where, C_D = Discharge coefficient

A_n= Injector orifice area

ρ_f= Density of the fuel

2.8.4. Break Thermal Efficiency

The percentage of break thermal efficiency of the engine (η_{th}) is related to engine break power (P) and the total energy input to the engine which is Q_{LHV} lower heating value of fuel in kJ/kg applied to the fuel consumption rate as:

$$\eta_{th} = \frac{p \times 100}{\dot{m}_f QLHV \times 3600} \times 100 \quad \text{..... (25)}$$

3. MATERIALS AND METHODOLOGY

Experimentation procedure is the only method used in this research paper.

The procedures used to enhance the experimental work are the following:-

1. Sample collection and preparation
2. Description of pyrolysis set-up
3. Production of oil by using pyrolysis process,
4. Distillation process,
5. Characterization of distilled waste tyre derived diesel using different parameters,
6. Testing the performance of the produced diesel in a four stroke diesel engine.

Since it was hard to set up the reactor tyre extractor by private manner, the sample collection, preparation and extraction of the fuel was done on the Hang Wa tyre oil industry factory. This company was advanced in production of tyre oil, black carbon and other means of product yields. And this study is mainly conducted on distillation of the extracted oil, testing and study the performance of the distilled oil with blended fuel and analyzing the emission characteristics in diesel engine.

3.1. Sample Collection from HTOIF

Fig. 12 shows sample collection, the samples of waste tyre were collected from legally land filled areas like waste tyre station in Debrezt (Bishouftu) town and from local area of illegal land filled in Addis Ababa.

Fig. 12: Sample collection of waste tyre

3.1.1. Sample Preparation at HTOIF

Collected samples were washed using laboratory sink and dried out. The sample was sorted out manually to determine its composition and they were cut in to small pieces less than 5mm in size approximately for liquefaction process using shredder machine. The following are the major steps in preparation of the sample.

i) **Collection of waste tyres**: All kinds of waste tyres were available, from small car tyres to big OTR tyres.

ii) **Removing steel wire**: Steel wire pulling machine was used to pull out the steel wire from waste tyres. The steel wire pulling machine was operated automatically, which only need one person for operation.

Fig. 13: Hang wa steel wire remover and its process

iii) **Shredding tyres**: A specialized tyre shredder was used to process big whole tyres into 3-5cm small pieces for easy feeding. The tyre shredder was a single and fully automatic shredding system.

Fig. 14: Hang wa scrap tyre shredder and shredded tyres

iv) **Pyrolysis process**: Shredded tyres were fed into the waste tyre pyrolysis plant. In the multiple pyrolysis reactor system the shredded tyre was pyrolyzed into oil gas.

Fig. 15: Hang Wa pyrolysis plant

3.2. Description of Pyrolysis Set-Up

Reactor

It was mild steel cylindrical reactor with capacity of 2.8m height and 3m width in size, 30 tons of System Equipment total weight, maximum 70KW/Hour of power consumption and water consumption of $60m^3$/hour. It is known as Fluidized bed reactor. Fluidized beds were typically used to perform fast pyrolysis (reaction time of milliseconds to seconds); fast pyrolysis requires small particle sizes. The fluidized bed was thus heated indirectly to typical temperatures of 500 °C–900 °C.

The reactor was heated externally by putting it inside an electrical furnace or charcoal. The bed temperature and the temperature of the vapor are measured using two thermocouples connected to a digital temperature indicator at suitable heights. The tubing ends were fitted with tapers and a stainless steel mesh at the joints to prevent large Particulates from escaping with the carrier gas.

During waste tyre pyrolysis the gaseous product that formed was continuously transported through the tube of a glass shell and tube condenser whereby counter-current running tap water in the shell was used as coolant.

Furnace

The heat source for the furnace used for the pyrolysis operation was a charcoal with the temperature being measured by K^1 type thermocouple fixed inside the reactor. The range of temperature of the reactor was external temperature controller. K^1 type thermocouple consists of two wires from one end and is made from chromium and aluminum that is connected to the temperature controller and the other end is a sensor connected to the reactor. It was used for sensing the temperature of the gaseous vapor inside the reactor.

Condenser

The condenser employed was a shell type counter flow heat exchanger with single pass.

- ✓ Number of tubes -6
- ✓ Length of the condenser -370 mm
- ✓ Tube diameter -9 mm

During the pyrolysis vapor from the reactor were made to pass over the tubes of the condenser and they get condensed due to continuous circulation of cold water through the

tubes. The liquid oil was collected in a glass container Shell diameter -75 mm. The Char and light oil weight (first condensation step) was measured and stored for analysis.

Due to the minimal product and its waxy nature the heavy oil (second condensation step) was difficult or in some cases not possible to collect and measure. The condensed oil product was collected in a 250 ml Buchner flask. The remaining non-condensable gas was passed through a further 250 ml Buchner flask which was connected to a bath where a yellow wax like substance was found sticking to the walls of the flask. The final gaseous part of the product was vented to the atmosphere through a fume hood.

Vacuum Pump

Vacuum was an important parameter in the tyre pyrolysis and the vacuum was measured using a vacuum gauge. Parameter in the tyre pyrolysis and a vacuum pressure of the range 450-600mm of Hg was maintained throughout the pyrolysis process using the vacuum pump.

3.3. Production of Oil by Pyrolysis Process

Oil was extracted from waste tyre by using pyrolysis process. The oil extraction or production of fuel oil using pyrolysis process was done in Oromia, Bishoftu town and it was led by Chinese company known as Hang Wa industrial oil factory. The factory had received much popularity in producing liquid fuels and a range of specialty and commodity chemicals. And beyond on that, this study was mainly conducted on distillation of the extracted oil, testing and study the performance of the distilled oil with blended fuel and analyzing the emission characteristics in diesel engine.

The experiment Pyrolysis was mainly involved the thermal degradation of tyre rubber at high temperatures in oxygen absent environment and under vacuum or atmospheric pressure. And it was performed under the operating condition of fast pyrolysis.

Fast pyrolysis was involved the rapid heating of the feed material to a high temperature (750–900°C) in the absence of oxygen with a short residence time of the condensable vapor in the reactor. In each unit of the pyrolysis process was taken 1000kg tires per reactor and it was treated in a 4-6 hour process.

Fig. 16 shows the schematic diagram of Hang wa industrial oil factory of the pyrolysis plant.

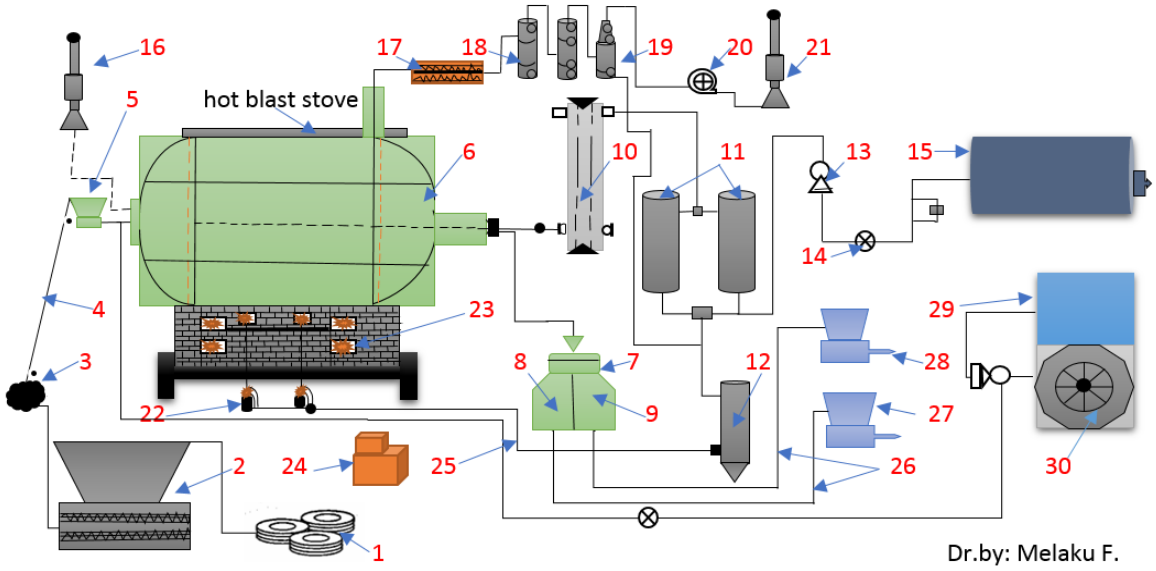


Fig. 16: Schematic diagram of Hang wa industrial oil factory of the pyrolysis plant.

Plant component part names:

1. Waste tyres
2. Tyre shredder machine
3. Shredded tyre pieces
4. Conveyer
5. Bunker
6. Pyrolysis reactor
7. Magnetic separator
8. Scrub steel product
9. Black carbon
10. Gas separator
11. Condenser
12. Hydro seal
13. Oil vacuum pump
14. Flow meter
15. Oil tank
16. Exhauster
17. Heat exchanger
18. Gas scrubber
19. De-dusting system
20. Draft fan
21. Chimney
22. Gas burner
23. Burning room
24. Controller
25. Burning line
26. Auto discharge system
27. Scrub steel wire discharger
28. Carbon black discharger
29. Cooling tank
30. Cooling tower

3.4. Simplified Work Flow of Tyre Pyrolysis Process

The overall waste tyre to oil pyrolysis plant working steps pyrolysis describes as follows:

1. Shredded and washed tire chips, approximately two inches by two inches, were received at the recycling facility. The chips were fed to an indirect rotary kiln using special conveyors and air seals. The reactor was supposed to be left 1/3 space for rotating more smoothly and the inlet door of feeding machine was closed to avoid from gas leakage.

2. Reactor was placed inside Furnace, and it was gently heated by burning the fuel material (coal and tire oil generated from last batch like charcoal). After evacuation process of oxygen, the thermal process starts. The oil gas was released when the temperature reached 750℃ (800-900℃ was the top output rate interval) and the gas by-products are generated.

3. The indirect kiln the pyrolysis reaction was carried out and the chips gone through three stages inside the kiln. First, the rubber becomes brittle and separates from the steel. This was known as a rubber char. In the second stage, the oil and gas were forced from the rubber char and swept from the kiln. In the last tire pyrolysis stage, the char was fully processed into a carbon black with mixture of scrub steel wire.

4. Heavy oil gas separated by manifold gas oil separator was supposed to be liquefied and drop down into the heavy oil fraction manifold. Then the lighter gas was rise up to the oil condensers, be liquefied in to oil and stored in the oil tank. . The condensable Hydrocarbon was collected as pyrolysis oil and available for filtration and then useable as heating oil, to generate power or Hydrogen production. The gas which couldn't be liquefied under normal pressure was designed to go back to combustion system through safety device. The non-condensable pyrolysis gas was flow through a Gas-Scrubber for desulfurization and cleaning, like a special filtration and thereafter pumped in a Gas pressure. Finally, the non-condensable gas through by hydro seal was led to the furnace for recycling to heat the reactor as fuel.

5. After all fuel oil was produced, the reactor was removed from oven and should been cool down. This was mainly required to replace a new batch and to discharge char mixtures. Carbon black was separated from the steel wires by magnetic separator and they discharged automatically when the temperature falls down 40℃. The char was sent through a Hollo-Flite processor (to cool & to clean it) and then the cleaned carbon char was transferred via bucket conveyor to a Milling/Grinding section. After grinding process the CB was transferred for finishing process to pelletizing equipment. Finally the pelletized CB (pellets/granule) was packaged into Jumbo bags or 20 kg sacks ready for selling and/or temporary storage. And the steel was cooled and the steel wires are compacted and made available for transport to a steel recycler or steel processing furnace.

6. Generally, to accomplish the above overall steps of pyrolysis process was guided by the following a typical cycle time.

Table 6: Pyrolysis typical time

Process	Time, Hours	Remark
Tyre feeding	2 to 3	
Reactor pre-heating	4 to 5	
Pyrolysis process time	6 to 8	At 750-900^{o}C
Reactor cooling	2 to 3	
Char and pellet discharging	4 to 5	
Packaging of carbon black pellet, oil, steel	---	Parallel process
Total	**18/24**	

a) Carbon black b) scrap steel wire c) crude oil

Fig. 17: Crude oil from waste tyre extracted by using pyrolysis process

3.5. Influence of various parameters on the yield of pyrolysis products

The composition of the pyrolysis products was influenced by the process operating conditions.

I. Temperature

Temperature was the predominant factor influencing the distribution of gas, liquid, and solid phase pyrolysis products and their physical/chemical properties. The pyrolysis temperature must be high enough to thermally degrade the tires; however, higher temperatures and long gas residence times in the reactor hot zone can volatilize the oil to gas. Thus, an optimal temperature exists for maximizing oil production was from 750-900 ^{0}C.

II. Feed size

Smaller feed size particles provide more reaction surface, giving high heating rate and rapid decomposition of rubber.

III. Pyrolysis time/Residence time

Pyrolysis time is related to particle size: in general, larger particles require longer residence times to achieve the same degree of conversion. Longer residence times require a larger reactor, with larger capital costs. Pyrolysis time is also linked to heating rate, with lower heating rates requiring longer pyrolysis times. An increase in vapor residence time decreases liquid and char yields while the gas yield increases slightly.

3.6. Precautions for Production Waste Tyre Fuel

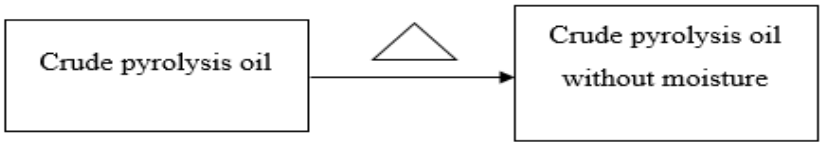
- Sizing and Weighing of sample intended for pyrolysis reactor should be sized and weighted carefully;
- Reactor should be thoroughly cleaned of any residues, before setting the sample in it;
- Condenser as well as measuring flask should be properly cleaned, to get rid of undesirable scattering or dust and chemicals present in them;
- Reactor should be properly fixed down to avoid loss of volatile component produced during Pyrolysis;
- During the process of Pyrolysis devoted observation should be made on the temperature controller.

3.7. Distillation Process

Distillation was a commonly used method for purifying liquids and separating mixtures of liquids into their individual components. Before getting the crude oil into distillation process, the following two pre-treatments are available.

1. Heating

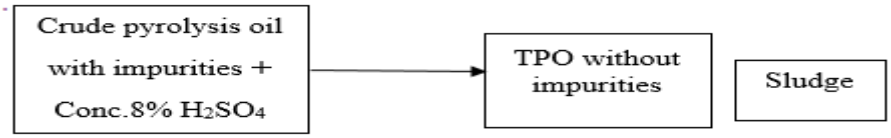
The oil obtained due to pyrolysis of waste tyres from the pyrolysis reactor is of crude nature, which contains impurities and moisture. This moisture has to be removed before subjecting the oil to any further chemical treatments. Hence, the oil is heated to above 100 ºC for (15 – 20) minutes, for getting rid of its moisture content.



i. Heating distillation process

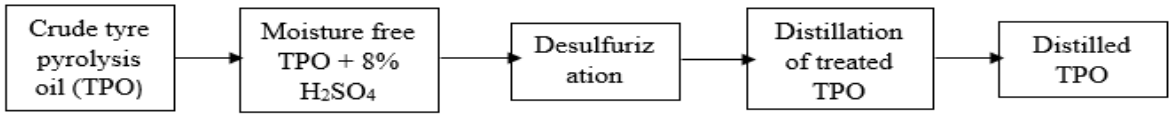
2. Treatment of crude oil with concentric H_2SO_4

The moisture free pyrolysis oil contains impurities in the form of excess carbon particles and Sulphur. Though Sulphur present in tyres cannot be removed completely, treatment with Conc.H_2SO_4 at least reduces the percentage of Sulfur in tyres. The oil is mixed with 8% of Conc.H_2SO_4, stirred well and left to settle for 40 hours without any disturbance. The impurities and excess carbon particles react with Concentric $H_2SO_4$and gets deposited at the bottom of the container in the form of sludge. The chemically treated oil is centrifuged at 2500 rpm in order to remove the sludge formed and pyrolysis oil without impurities is obtained.



ii. Treatment of crude conc.H_2SO_4 with DTPO

Finally the distillation is being to start;



a) Distillation process b) crude tyre oil c) diesel tyre oil

Fig. 18: Distillation process of crude tyre oil at (200-270 ^{0}C)

3.8. Characterization of Waste Tyre Derived Diesel Fuel

Characterization is the process of determining the physiochemical properties of petroleum products or mixture of petroleum and non-petroleum products. Before testing the performance of the produced fuel in diesel engines, it is very important to know its physiochemical properties.

Characterization of the waste tyre fuel to be tested in these experiments was carried out at the laboratory of Ethiopia petroleum supply enterprise (EPSE). Fuel properties of tested sample were determined in accordance with American standard for testing materials (ASTM) procedures for petroleum products in the book of ASTM, 2002.

Without distillation process, testing the crude tyre oil in diesel engine is terrible proscribed. And to manage this issue I was distilled the tyre oil in properly manner and supplementary gone to characterized its properties. The procedure characterization was mainly examined the DTPO itself and the DTPO blended with B20. This was selected because of B20 is the better fuel blend proportion feat for running any diesel engine rather than the other blends except B10. But the reason why the B10 wasn't selected on this study is since the previous researcher was examined the TPO with B10 to run in diesel engine.

Comprehensive analysis was carried out to document fuel properties of the tested sample. Each fuel sample was evaluated to determine the density, viscosity, flash point, distillation, copper strip corrosion, and specific gravity. Various apparatus were employed in the determination of these fuel properties.

The properties of fuel were studied following the procedure for each property given in the ASTM book.

Fig. 19: Sample of waste tyre fuels

3.8.1. Determination of relative density (Sp.gr) and API gravity (ASTM D4052)

Specific gravity and density of each sample was measured using hydrometer. Density and relative density are factors governing the quality and pricing of crude petroleum. The sample fuel was filled into graduated cylinder and its temperature was recorded. The appropriate hydrometer is lowered in to the sample and allowed to settle and it was inserted into the fuel to measure the SG of the fuels specified. After temperature equilibrium has been reached, then temperature correction factors (according to tables from (ASTM D 1250-80, 1980; petroleum tables, 1963)) were applied to convert the measured specific gravities to the reference temperature of 60/60^{0}F and densities were taken at temperatures of 15 ^{0}C and 20 ^{0}C.

The API gravity is calculated from the relation:-

$$\text{API gravity} = \frac{141}{\text{Sp.gr}60/60^{o}\text{F}} - 131.5 \quad \ldots\ldots (26)$$

The American petroleum institute gravity, or **API gravity** is a measure of how heavy or light petroleum liquid is compared to water. If its API gravity is greater than 10, it is lighter and floats on water, if less than10, it is heavier and sinks. API gravity is thus an inverse measure of the relative density of a petroleum liquid and the density of water, but it is used to compare the relative densities of petroleum liquids. The instrument used is shown in figure 26.

Fig. 20: Measuring Sp.gr and density

3.8.2. Determination of flash point (ASTMD93)

Flashpoint is the lowest temperature at which a product gives off just sufficient vapor to form a flammable mixture with air understands condition. The flashpoint of diesel in not directly related to engine performance. It is however, important in connection with safety precautions and legal requirements involved in fuel handling and storage.

Goods storage and handling and transportation regulations, and is specified to comply with fire regulations and insurance requirements. The flash points were measured with a pen sky-martens closed cup tester using ASTM D93, standard test methods. The apparatus used is shown in figure 22.

The apparatus and methods consist of the controlled heating of fuel similar to diesel sample in a closed cup, introducing an ignition source, and observing if the heated sample fuels similar to diesel flasher. The temperature at which the sample fuel similar to diesel flashes is recorded as the flash point [23].

Correction of flash point:

By recording the ambient barometric pressure during the time of test,

Corrected Flash Point (CFP) = T + 0.25 (101.3 – K)

Corrected Flash Point (CFP) = T + 0.033 (760 – P)

Corrected Flash Point (CFP) = F + 0.06 (760 – P)

Where, T = Observed Flash Point Temperature (^{0}C)

K = Ambient Barometric Pressure (kPa)

P = Ambient Pressure (mmHg)

F = Observed Flash Point (^{0}F)

Fig. 21: Apparatus for determination of flash point

3.8.3. Determination of cloud point (CP) (ASTM D2500)

The cloud point of petroleum product is an index of the lowest temperature of its utility of certain applications and it is measured as shown in the fig. 23 using ice pack. Mixtures commonly used for temperature reduction are the following:-

I. Ice and water up to 10^0C.

II. Crushed ice and sodium chloride crystals, up to - 12^0C.

III. Crushed ice and calcium chloride crystals up to – 26^0C.

IV. Acetone, Methyl or Ethyl chloride or petroleum naphtha chilled up to – 57^0C [27].

Cloud point was determined using ASTM D2500, standard test method for cloud point of petroleum products. The cloud point was determined by visually inspecting for a cloud in the normally clear fuel, while the fuel was cooled under carefully controlled condition. The sample was continuously monitored and the temperature (^{0}C) that corresponds to the first formation of a cloud in the fuel was recorded [23].

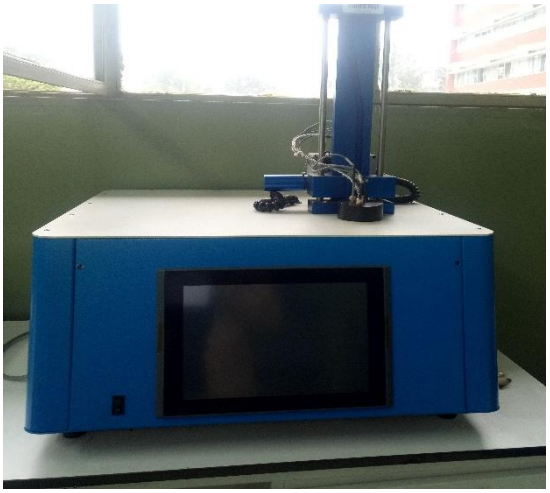


Fig. 22: Apparatus measuring cloud point

3.8.4. Determination of copper strip corrosion 3hrs @100^{0}C (ASTM D130)

The test helps to determine the suitability of a lubricant for use in equipment containing copper-based components. It may also be used with silver bearing metals. Cutting fluid used in the machining of non-ferrous materials should be non-corrosive. The copper strip corrosion test is designed to assess the relative degree of corrosively of a Petroleum product due to active sulfur compounds.

The Copper Corrosion test is a widely used oil analysis method for gearbox, turbine and hydraulic lubricants. This oil analysis method will detect the corrosive effects of a lubricant on copper alloys, but it is ineffective on iron or ferrous alloy parts and components. The copper corrosion oil analysis method, ASTM D130, is relatively simple. A polished Copper strip is immersed in 30mL of sample at elevated temperature, 50 °C or 100° C, depending on the type of gasoline, grease or oil tested, for a period of three hours. At the end of this period, the copper strip is cleaned and examined for evidence of degradation. Results are rated by comparing the stains on the copper strip to the ASTM color-match scale from 1A to 4C [ASTM Standards, 2002].

Fig. 23: Apparatus for determination of corrosion strip corrosion 3hrs @100^{0}C.

3.8.5. Determination of kinematic viscosity (ASTM D445)

Kinematic viscosity of tyre fuel similar to diesel was determined using ASTM D445, standard test methods for kinematic viscosity of transparent and opaque liquids.

Canon Fenske glass capillary tube was used in a SETA KV-8 viscometer bath. Sample fuel is filled in the capillary viscometer tube and kept for 30 minutes to maintain equilibrium temperature of 40^{0}C. The time (t) is recorded for a fixed volume of liquid to flow under gravity through the capillary of a calibrated viscometer. Kinematic viscosity is then calculated as the product of this time (t) in seconds and the calibration constant (K) of the viscometer tube using the equation

kinematic Viscosity = K * t……..... (23)

Where, K = Calibration constant for the viscometer in (mm^2/s^2)

t = Time in (s)

Fig. 24: Apparatus for determination of kinematic viscosity

3.8.6. Determination of ash content (ASTM D482)

A small sample of fuel is burned in a weighted container until all of the combustible matter has been consumed. The carbonaceous residue was reduce to an ash by heating in a muffle

furnace at 800^{o}C, cooled and weighed, reported as 0.011% by weight of the fuel. Ash contributes to wear in the fuel system and plugging of the filters and nozzles. It can also increase the deposit level in the engine, which contributes to overall wear increase.

Fig. 25: Apparatus for determination of ash content

3.8.7. Determination of water and sediment, V/V %(ASTM D2709)

This test method covers the determination of the volume of free water and sediment in middle distillate fuels having viscosities at 40°C (104°F) in the range of 1.0 to 4.1 mm 2/s (1.0 to 4.1 cSt) and densities in the range of 770 to 900 kg/m3. Appreciable amounts of water and sediment in a fuel oil tend to cause fouling of the fuel-handling facilities and to give trouble in the fuel system of a burner or engine. An accumulation of sediment in storage tanks and on filter screens can obstruct the flow of oil from the tank to the combustor. Water in middle distillate fuels can cause corrosion of tanks and equipment, and if detergent is present, the water can cause emulsions or a hazy appearance. Water is necessary to support microbiological growth at fuel water-interfaces in fuel systems.

Fig. 26: Apparatus for determination of water and sediment, V/V %

3.8.8. Determination of total acidity, mg KOH/g (ASTM D974)

This working procedure deals with the titration of Total Acid Number (TAN) in oil. The working procedure determines the sum of all acid compounds present in petrochemical samples by an acid-base titration using KOH as titrant. TAN is expressed in mg of KOH per g of sample.

Since samples are non-aqueous, they are diluted in a mix of chloroform and isopropyl alcohol. The solvent for KOH is isopropyl alcohol.

Fig. 27: Apparatus for determination of total acidity, mg KOH/g

3.8.9. Determination of total sulfur, %wt (ASTM D4294)

This test method covers the determination of total sulfur in petroleum and petroleum products that are single-phase and either liquid at ambient conditions, liquefiable with moderate heat, or soluble in hydrocarbon solvents. These materials can include diesel fuel, jet fuel, kerosene, other distillate oil, naphtha, residual oil, lubricating base oil, hydraulic oil, crude oil, unleaded gasoline, gasohol, biodiesel (see Note 2), and similar petroleum products.

Fig. 28: Apparatus for determination of total sulfur, %wt

3.8.10. Determination of color (ASTM D1500)

ASTM Color as specified in ASTM D1500 is a single number colour scale for grading petroleum products. The scale is defined by 16 glass standards of specified luminous transmittance and chromaticity, graduated in steps of 0.5 from 0.5 for the lightest colour to 8.0 for the darkest. It is intended for a variety of petroleum products such as lubricating oils, heating oils, diesel fuel oils, mineral insulating oil and solid petroleum waxes and has been adopted by other standardising bodies [24].

Fig. 29: Apparatus for determination of color

3.9. Performance Test

The experimental work was carried out using a chassis dynamometer and the performance of diesel vehicle equipped with 4 cylinder, 4 stroke diesel engine with B0, DTPO and B20 as fuels was tested in Adama Science and Technology University in mechanical and vehicle engineering department workshop. This test was done to show a comparison between tyre derived fuels similar to diesel and regular diesel for wheel power and tractive force, keeping the other parameters constant for both fuel types.

3.9.1. Pre-test procedures

Before testing, a variety of checks and tasks have been carried out. The engine was inspected visually for any problems, the engine coolant was filled to the optimum level in the expansion tank, the air intake system and test area were cleaned properly.

Additionally, the engine was properly warmed up prior to tests for two reasons. First, the engine can be damaged if run under high loads before reaching proper operating temperature. Second, torque, power, fuel flow and many other types of readings tend to fluctuate

depending on engine temperature. Once the engine reaches operating temperature (in this case 75^0C cooling water temperature), the readings will be reliable.

3.9.2. Post-test procedures

After full load testing, the engine was idled down for at least five minutes in order to stabilize the internal engine temperature for all types of fuel test. When switching from one fuel test to the next, the engine was allowed to operate at least for 10 minutes before starting the test in order to ensure the complete consumption of leftover primarily tested fuel in the fuel system and its smoother operation with the new fuel.

3.9.3. Data analysis

From the experiment wheel power and tractive force data were collected. These data were tabulated in accordance with specified respective vehicle speed. The bsfc was calculated manually from the gram of fuel consumed at a given duration of time and engine brake power.

From this data graphs which indicate performance characteristics were plotted, by using computer program Microsoft XL. Finally the comparison of overall performance characteristics was done with specific standard value of diesel fuel on a given test engine.

4. RESULTS AND DISCUSSION

4.1. Important properties of waste tyre oil diesel and tested diesel fuel

The extraction process was done by pyrolysis method. In this process, waste tyre pieces were crushed and shredded with pyrolysis utensils of shredder machine. And the waste tyre crude oil was extracted by the pyrolysis reactor for the range of (300 - 700)^{0}C medium temperatures and high temperature (750-900)^{0}C in oxygen-free environment to decompose solid tire wastes chemically in to char, oil, and gas. The result of the experimentation from the Hang Wa tyre oil industry factory for the extracted crude oil was examined like as shown in table 7.

Table 7: Properties of waste tyre oil after extracted [HTOIF]

SN.	Properties	Tyre pyrolysis oil
1	Density @ 15 ^{0}c , (Kg/L)	0.956
2	Kinematic viscosity @40 (mm^2/s)	3.2
3	Pour point	-3.00
4	Flash point	50
5	Gross calorific value (kJ/kg)	42.83
6	C (wt %)	85.65
7	H (wt %)	10.04
8	S (wt %)	1.15
9	N (wt %)	1.15
10	O (wt %)	0.25

The filtered crude oil sample was tried for distillation. By taking 3000 ml of the oil, the exact and appropriate reaction temperature range of (200-270) ^{0}C was reached after some trials of each 3000 ml oil sample to diesel oil. Table 8 shows the experimental data for distilled oil procurement at different temperature.

Table 8: Experimental data for distilled oil procurement at different temperature

Time (min)	Temperature (^{0}C)	Total amount of oil received (ml)
0	30	0
10 -50	123	410
60-100	178	1985
110-150	214	2230
160-200	246	2750
210-250	270	3000

The fuel characterization result shown in table 10 indicates that there is small deviation in most properties for tyre waste oil derived diesel from that of tested diesel fuel. The most important diesel property that depends on types of feed stock and appropriate distillation process is viscosity. This property could affect the fuel flow in fuel lines, the droplet formation and atomization which are directly to complete combustion and utilization of fuel energy.

The result of the experimentation as shown in the table below all the parameters are tested as to the test method indicated and all have satisfied the above requirement and all the parameters are obtained in the accepted range as shown below when compared to the values of ASTM standard test method.

Table 9: important properties of tested neat diesel fuel and blended waste tyre diesel

SN.	Property	Test method ASTM	EPSE diesel limits	Source From (HTOIF)	Test result	
				Crude TPO	(DTPO), (B0)	Blend DTPO (B20)
1	Density @ 15 ^{0}c, (g/ml)	D4052	Report	0.956	0.8311	0.8527
	Density @ 20^{0}c, (g/ml)	D4052	Report	0.906	0.8275	0.8492
2	Flash point (PMCC) , min	D93	Min. 66	50	94	73

3	Copper strip corrosion 3hrs @100 ^{0}c	D130	Max No. 1		1A	1A
4	Cloud point, ^{0}c	D2500	Max. +5		-2	0
5	Kinematic viscosity @40 (mm^2/s)	D445	2.0-4.5	3.2	3.85	3.98
6	Water and sediment, V/V %	D2709	Max. 0.05		<0.05	<0.05
7	Total acidity, mg KOH/g	D974	-------		0.16	0.10
8	Ash content, %wt	D482	Max. 0.01		0.005	0.004
9	Total sulfur, %wt	D4294	Max. 0.05	0.055	0.0161	0.0426
10	Color	D1500	Max. 2	4.5	3	1.5

4.2. Performance Characteristics

Fig. 33 shows the chassis dynamometer gauge and diesel vehicle (engine model 3L Toyota 2779cc) for performance testing. The engine performance test results using conventional diesel fuel and blends are presented in the figure below. The power and torque curves pattern of the fuel blends against the speed seems to be similar to the conventional diesel fuel. The slight reduction in power and torque is due to the lower calorific value of the diesel.

Fig. 30: Chassis dynamometer for vehicle (engine) performance testing.

The measured value of tractive effort (F) in kN of fuel from chassis dynamometer is used for calculating the torque at the rear wheel and furthers also the brake torque. The following data shows the measured wheel force and power for (DTPO/B100), blended diesel of B20/DTPO) and pure conventional diesel (B0) fuel at 4th gear.

Table 10: Wheel force at 4th gear (kN)

Speed (Km/h)	Automotive Diesel Oil (B0)	DTPO (B100)	Blend DTPO (B20)
30	1.4	1.36	1.38
35	1.35	1.3	1.34
40	2	1.5	1.8
45	1.1	0.9	1
50	0.9	0.8	0.85
55	0.84	0.78	0.8

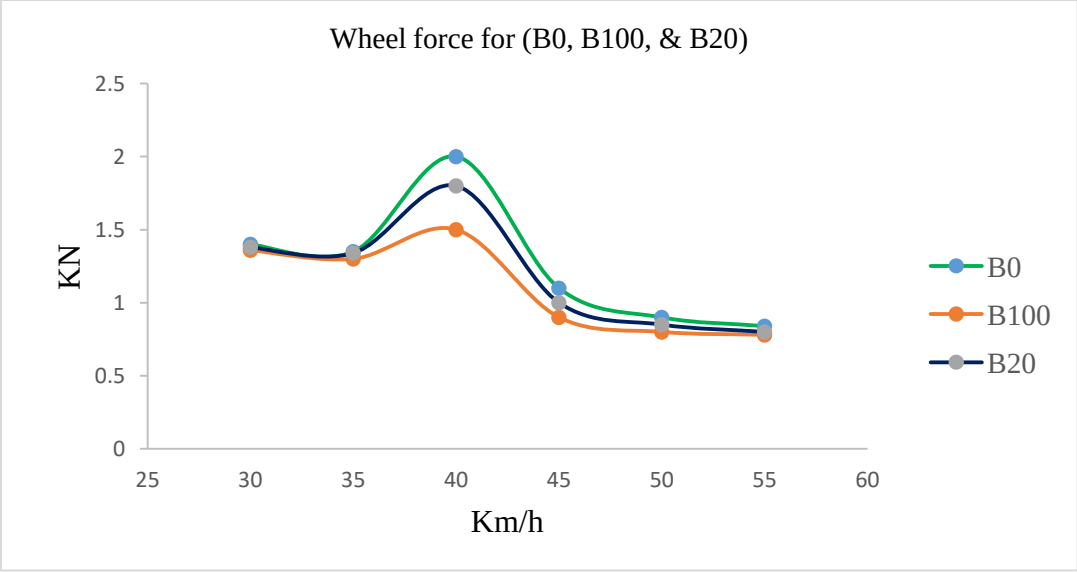


Fig. 31: wheel force characteristics at 4th gear

Table 11: Wheel power at 4th gear (kW)

Speed (Km/h)	Automotive Diesel fuel (B0)	DTPO (B100)	Blend DTPO (B20)
30	11.5	8.5	10.7
35	14.5	12	13.8
40	17	14.9	16.5
45	9.5	8.5	9.3
50	9	7.8	8.5
55	6.5	5	7.5

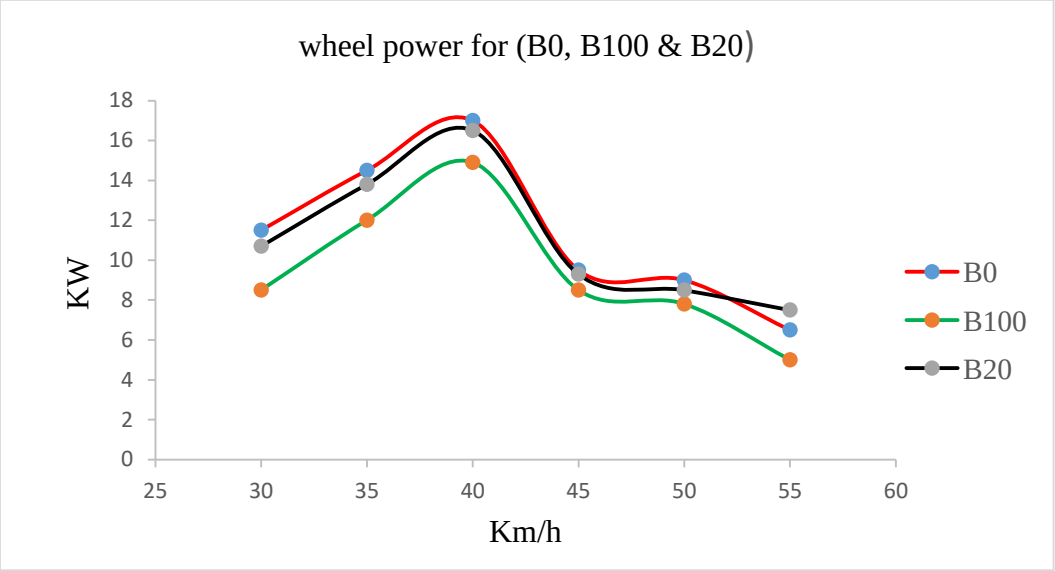


Fig. 32: wheel power characteristics at 4th gear

Generally Fig. 34 and 35 shows the performance (wheel force and wheel power) results from table 11 and 12 for four stroke four cylinder diesel engine vehicle tested on chassis dynamometer for DTPO (B0), DTPO (B20) and diesel fuels.

i. **Engine speed (N):** $N = 2.65 \times \frac{GRt}{rw} \times V$

Where, N = Engine speed in 'rpm'

V = Vehicle speed in 'Km/h'

r_w= Radius of wheel in 'm'

GR_t = Total gear ratio and it is given by:

$GR_t = GR_i \times GR_f$

Where, GR_i=Specified gear ratio,i = 1, 2, 3…

GR_f = Final drive gear ratio

The testing performance of DTPO and its blended was tested in chassis dynamometer then the parameter performance for engine speed was not clearly assigned by vehicle dashboard. Therefore, due to that using the gear specification of the car at 4^{th} gear and at various vehicle speed the engine speed was calculated as follows.

$$N_1 = 2.65 \times \frac{GRi \times GRf}{rw} \times V_1$$

$$= 2.65 \times \frac{1 \times 4.3}{0.3} \times 30$$

$$= \underline{1140 \text{ rpm}}$$

$$N_2 = 2.65 \times \frac{GRi \times GRf}{rw} \times V_2$$

$$= 2.65 \times \frac{1 \times 4.3}{0.3} \times 35$$

$$= \underline{1329 \text{ rpm}}$$

$$N_3 = 2.65 \times \frac{GRi \times GRf}{rw} \times V_3$$

$$= 2.65 \times \frac{1 \times 4.3}{0.3} \times 40$$

$$= \underline{1519 \text{ rpm}}$$

$$N_4 = 2.65 \times \frac{GRi \times GRf}{rw} \times V_4$$

$$= 2.65 \times \frac{1 \times 4.3}{0.3} \times 45$$

= 1709 rpm

$N_5 = 2.65 \times \frac{GRi \times GRf}{rw} \times V_5$

$= 2.65 \times \frac{1 \times 4.3}{0.3} \times 50$

= 1899 rpm

$N_6 = 2.65 \times \frac{GRi \times GRf}{rw} \times V_6$

$= 2.65 \times \frac{1 \times 4.3}{0.3} \times 55$

= 2089 rpm

Table 12: Engine speed in RPM

SNO.	1	2	3	4	5	6
V in kM/h	30	35	40	45	50	55
N in rpm	1140	1329	1519	1709	1899	2089

Where, table 12 shows the converted vehicle speed in Km/h to engine speed in rpm.

ii. Engine brake power (P_b): $P_b = \frac{Pw}{\eta t}$

Where, P_b=Engine brake power in 'kW'

P_w = Wheel power

η_t = Total gear efficiency

And $\eta_t = \eta_i \times \eta_{fd}$

Where, η_i= Efficiency of specified gear, η_i= 0.875

η_{fd} = Efficiency of final drive, η_{fd} = 0.92 (source: from 3L toyta 2797cc car specification and text book references at 4th gear)

P_{b1} @ ($V1$ = 30 km/h & Pw1 =11.5kW),

$$P_{b1} = \frac{11.5}{0.875 \times 0.92}$$

$$= \underline{\underline{14.3\ kW}}$$

In the same way we can find P_{b2}, $P_{b3,}$ … and P_{b6} finally we will get:

Table 13: Engine brake power for B0

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
P_b in kW	14.3	18	23.539	11.8	11.18	8.07

Table 14: Engine brake power for (B100)

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
P_b in kW	10.559	14.9	18.5	10.559	9.689	6.21

Table 15: Engine brake power for (B20)

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
P_b in kW	13.04	17.143	20.496	11.55	10.559	9.32

Generally from table 13 to 15 shows the calculated engine brake power for all tested fuels (ADO (B0), DTPO (B100) and DTPO (B20)) at different engine speed.

iii. Engine brake torque (T_b): $Tb = \frac{Pb}{\omega w}$

Where, Tb = Engine brake torque

P_b= Engine brake power

ω_w = Angular velocity of wheel, $\omega_w = \frac{2\pi N}{60}$

$$T_b = \frac{60 \times Pb \times 1000}{2\pi N}, \; T_b \text{in 'Nm'}$$

T_{b1} @ (P_{b1}=14.3 kW & N_1=1140 rpm)

$$T_{b1} = \frac{60 \times Pb1 \times 1000}{2\pi N1}$$

$$= \frac{60 \times 14.3 \times 1000}{2\pi \times 1140}$$

$$= \underline{119.78 \text{ Nm}}$$

Table 16: Engine brake torque for B0

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
T_b in Nm	119.78	129.335	147.97	65.93	56.22	36.889

Table 17: Engine brake torque for (B100)

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
T_b in Nm	88.448	107.06	116.3	59	48.72	28.34

Table 18: Engine brake torque for (B20)

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
T_b in Nm	109.23	123.178	128.85	64.54	53.096	42.6

iv. Brake specific fuel consumption (bsfc):

Bsfc= $\frac{\boldsymbol{Amount\ of\ fuel\ consumed\ (g)}}{\boldsymbol{Brake\ power\ (kw)\times Durationtime\ (h)}}$, $[\frac{g}{kWh}]$

$Bsfc_1$ = @ (Consumed=240g, t=0.1667h & P_{b1}=14.3kW)

$Bsfc_1 = \frac{240g}{Pb1\times t}$

$= \frac{240g}{14.3kW\times 0.1667h}$

=<u>100.67 g/kWh</u>

Table 19: Brake specific fuel consumption for B0

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
Gram (g)	240	228	224	210	179	168
BSFC in g/kWh	100.67	75.98	57.085	106.75	96.045	124.88

Table 20: BSFC for (B100)

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
Gram (g)	300	320	318	286	306	305
BSFC in g/kWh	170.44	128.8	103.11	162.48	189.455	294.63

Table 21: BSFC for (B20)

SNo.	1	2	3	4	5	6
N in rpm	1140	1329	1519	1709	1899	2089
Gram (g)	335	296	278	223	245	232
BSFC in g/kWh	154.11	103.57	81.365	115.8	139.189	149.33

Table 22: Combined data for engine P_b, T_b and BSFC of B0

SNo.	N(rpm)	Automotive Diesel Oil (B0)		
		P_b (kW)	T_b (Nm)	BSFC (g/kWh)
1	1140	14.3	119.78	100.67
2	1329	18	129.335	75.98
3	1519	23.539	147.97	57.085
4	1709	11.8	65.93	106.75
5	1899	11.18	56.22	96.045
6	2089	8.07	36.889	124.88

Table 23: Combined data for engine P_b, T_b and BSFC of DTPO-B0

SNo.	N(rpm)	B100		
		P_b (kW)	T_b (Nm)	BSFC (g/kWh)
1	1140	10.559	88.448	170.44
2	1329	14.9	107.06	128.8
3	1519	18.5	116.3	103.11
4	1709	10.559	59	162.48
5	1899	9.689	48.72	189.455
6	2089	6.21	28.34	294.63

Table 24: Combined data for engine P_b, T_b and BSFC of B20

SNo.	N(rpm)	Blended DTPO B20		
		P_b (kW)	T_b (Nm)	BSFC (g/kWh)
1	1140	13.04	109.23	154.11
2	1329	17.143	123.178	103.57

3	1519	20.496	128.85	81.365
4	1709	11.55	65.54	115.8
5	1899	10.559	53.096	139.189
6	2089	9.32	42.6	149.33

4.2.1. Power characteristics

Figure 40 illustrates the engine brake power output at low to high engine rpm. DTPO-B0 is less brake power output low and high engine speed from all fuels. DTPO-B20 is maximum brake power output at low and high engine speed rather than DTPO-B0. Results in brake power output increases as engine speed increasing at some extent and then reduces as the speed engine approaches in middle range and then it increases more as increasing the engine speed during the test.

A close resemblance occurred at low and high speed indicating little difference in output b/n the fuels.

Table 25: Combined data for engine brake power

SNo.	N(rpm)	B0 P_b (kW)	B100 P_b (kW)	B20 P_b (kW)
1	1140	14.3	10.559	13.04
2	1329	18	14.9	17.143
3	1519	23.539	18.5	20.496
4	1709	11.8	10.559	11.55
5	1899	11.18	9.689	10.559
6	2089	8.07	6.21	9.32

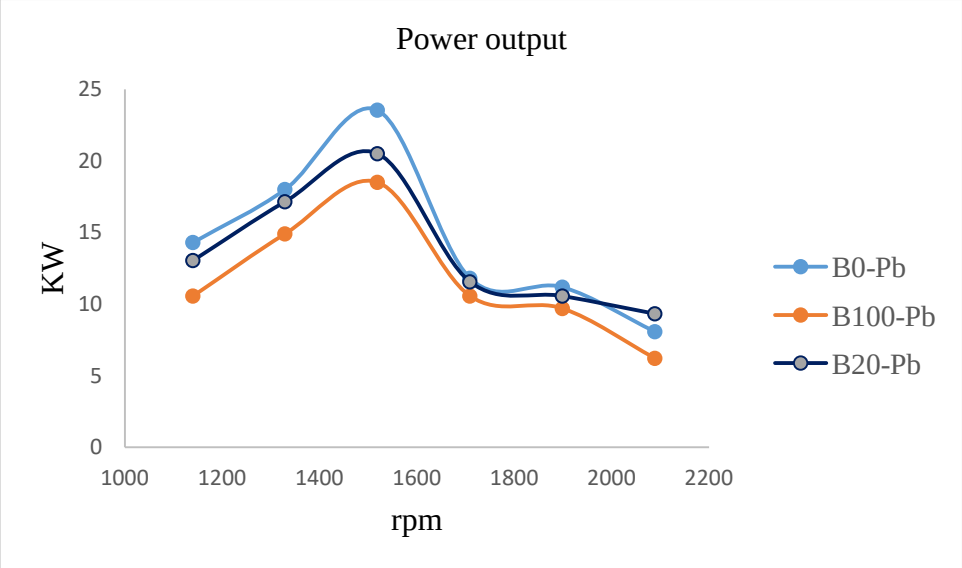


Fig. 33: Power output characteristics:

As ASTM D445 experiment performance specified all B0, B100 and B20 almost as similar pattern was quantified adequately. However the overall brake power reduction for all fuels was expected in a little variation due to the slightly small deviation in viscosity parameter. As the fuel viscosity increases it requires higher injection pressures to break fuel drops in to very fine droplets, conventional diesel engine fuel system is designed for lower viscous diesel fuel and it is not exactly fit for higher viscous fuels. Hence larger the original drop size emitted by the injector, the quicker and more efficient atomization process will not occur. If the atomization is not efficient as required, the small droplets of liquid fuel evaporate to vapor slowly as compared to low viscous fuel. Due to this the fuel vapor mixing with in the combustible A/F ratio will be delayed and associated self-ignition to provide complete combustion will be less efficient, thus comparatively lower fuel conversion efficiency can be achieved.

4.2.2. Torque characteristics

Table 26: Combined data for engine brake torque

SNo.	N(rpm)	B0 T_b (Nm)	B100 T_b (Nm)	B20 T_b (Nm)
1	1140	119.78	88.448	109.23
2	1329	129.335	107.06	123.178
3	1519	147.97	116.3	128.85

4	1709	65.93	59	65.54
5	1899	56.22	48.72	53.096
6	2089	36.889	28.34	42.6

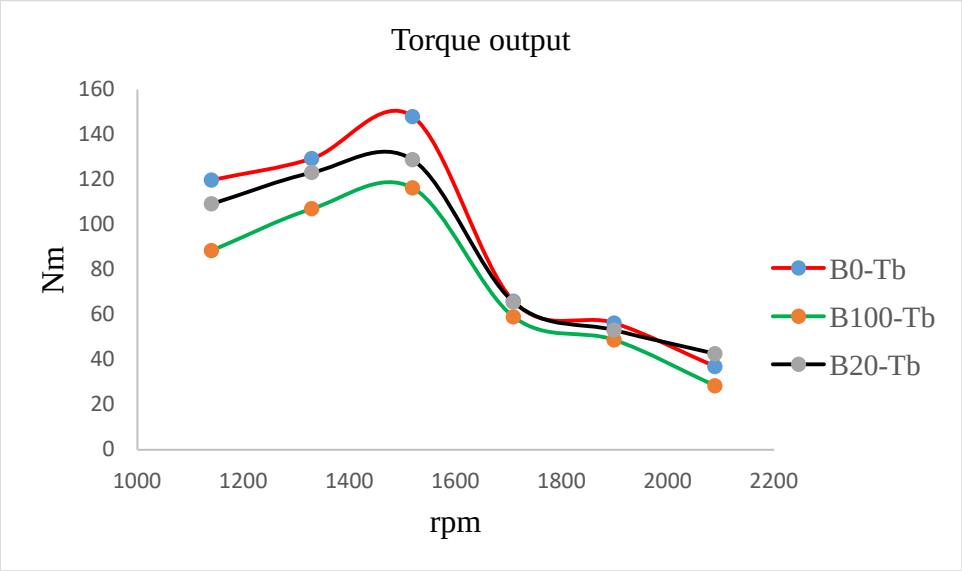


Fig. 34: Torque output characteristics

As figure 41 demonstrates similar variation to power characteristics were observed, similarly the maximum power and the maximum torque was obtained at middle range of rpm around 1519 rpm. However, the torque variation among diesel fuel and the rest other fuels was slightly higher at low to medium speed and close pattern was observed at maximum rpm operations.

From the experimental test using base fuel and the alternative fuels as engine speed is increasing from medium rpm to upper rpm the brake torque output is continuously decreasing as engine speed increasing.

However, the brake torque variations among B0, B100 and B20 fuels was slightly similar from the lower to higher engine speed and closer pattern was observed at higher rpm operations.

4.2.3. BSFC Characteristics

The fuel consumption is determined by measuring the amount of gram consumed by the engine for the given time (10min.) and brake power.

In this study, the brake specific fuel consumption (BSFC) was taken as a performance indicator to compare the fuels. Figure 42 shows the BSFC plots with engine speed for the fuels. Automotive diesel fuel had the lowest BSFC throughout the test. The BSFC for B100 and B20 was higher at lower speeds and slightly lower consumption was observed at higher engine rpms.

Table 27: Combined data for engine BSFC

SNo.	N (rpm)	B0 BSFC (g/kWh)	B100 BSFC (g/kWh)	B20 BSFC (g/kWh)
1	1140	100.67	170.44	154.11
2	1329	75.98	128.8	103.57
3	1519	57.085	103.11	81.365
4	1709	106.75	162.48	115.8
5	1899	96.045	189.455	139.189
6	2089	124.88	294.63	149.33

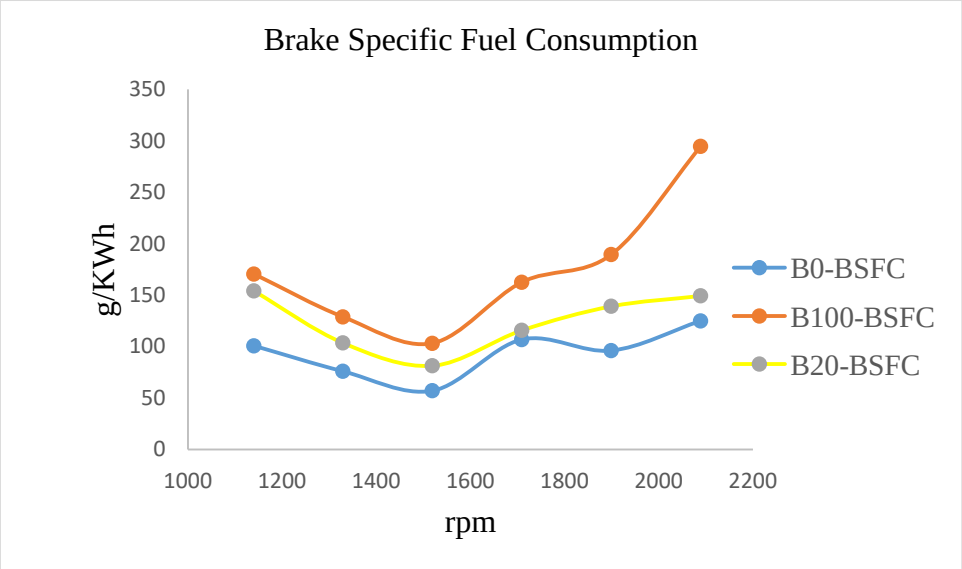


Fig. 35: BSFC characteristics

The curves showed that the specific fuel consumption at low speeds is high. During the engine testing the sample fuel was added to fuel holder simultaneously until it runs the chassis then occupationally data was become varies. Due to that case, all the parameter curve data of the brake power, brake torque and fuel consumption at the medium range of the engine speed becomes lower.

While, it is possible to see that the trend of the curves for B100 and B20 fuels are similar and comparable with that of the automotive diesel fuel. But the BSFC of B100 increases when it compared with B20 as the percentage of the fuel increase.

4.3. Emission characteristics test

Gas emission testing is a process of analyzer test equipment which is used to measure the gasses produced by a car's engine exhausts. The NOx, CO, HC and CO2 emissions of diesel engine operated on DTPO, diesel and blended diesel of DTPO were analyzed by Automobile emission gas analyzer gas board- 5020.

Gas board -5020, emission gas analyzer can be used for measurement of the concentration of automobile emission gases based on the pulsable infrared source and single source two beams non-dispersion infrared method, this analyzer is designed with portable and smaller physical dimensions.

Since the equipment was not available in ASTU, the emission test was verified at Adiss Abeba HTOIF branch two. Fig. 43 shows that the gas board -5020 emission gas analyzer.

Fig. 36: Exhaust gas emission tester

4.3.1. Nitrogen oxide emissions:

The fundamental mechanisms behind NOx formation in diesel engines are thermal, prompt, and fuel-bound nitrogen. One of the sources of nitrogen for NOx formation during combustion of diesel and alternative fuels is atmospheric (molecular) nitrogen. Thermal NOx refers to the NOx formed through the high temperature oxidation of nitrogen (N2) in the combustion chamber. NO emission formation in diesel engine is driven by the following key parameters i.e. in cylinder temperature, air/fuel ratio, oxygen concentration and residence time for the reaction to take place.

Table 28: NO_X emission data

Engine speed, (rpm)	NO_X emission (ppm)		
	B0	B100	B20
600	320	330	328
1000	472	480	478
1400	676	690	550
2000	501	530	502

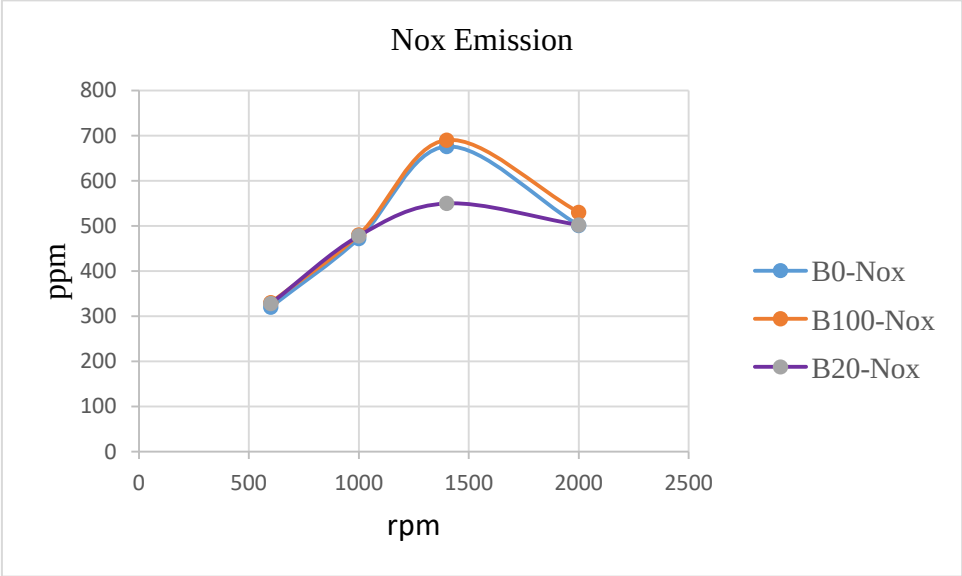


Fig. 37: NOx emission characteristics

4.3.2. CO and CO_2 emissions:

CO emissions are the result of incomplete combustion typically due to a lack of oxygen or available time in the cycle for the completion of combustion. In general, an increase in engine load or speed results in a decrease in CO emissions; however, an excessive increase in engine speed results in higher CO emissions. At very high engine speeds, a lower combustion fame temperature limits CO oxidation into CO_2; therefore, the CO emission values at very high engine speeds tend to also be higher.

A. CO emission:

Table 29: CO emission data

Engine speed, (rpm)	CO emission (%)		
	B0	B100	B20
600	0.06	0.08	0.072
1000	1.02	1.03	1.024
1400	1.04	1.06	1.014
2000	0.52	0.6	0.55

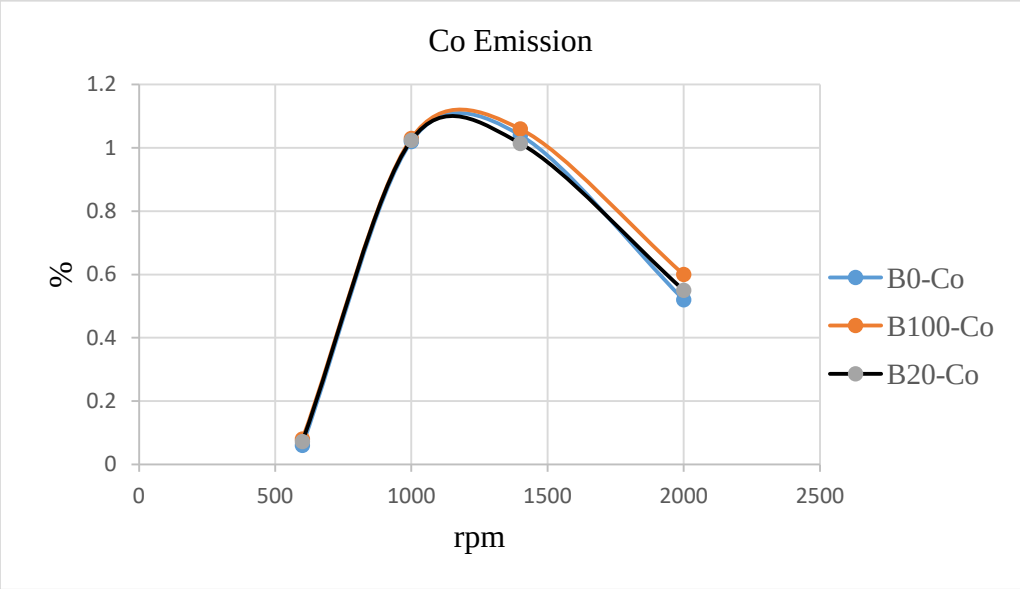


Fig. 38: CO emission characteristics

B. CO_2 emission:

Table 30: CO_2 emission data

Engine speed, (rpm)	CO_2 emission (%)		
	B0	B100	B20
600	0.3	0.38	0.35
1000	2.2	2.23	2.22
1400	3	3.4	3.2
2000	2.5	2.8	2.6

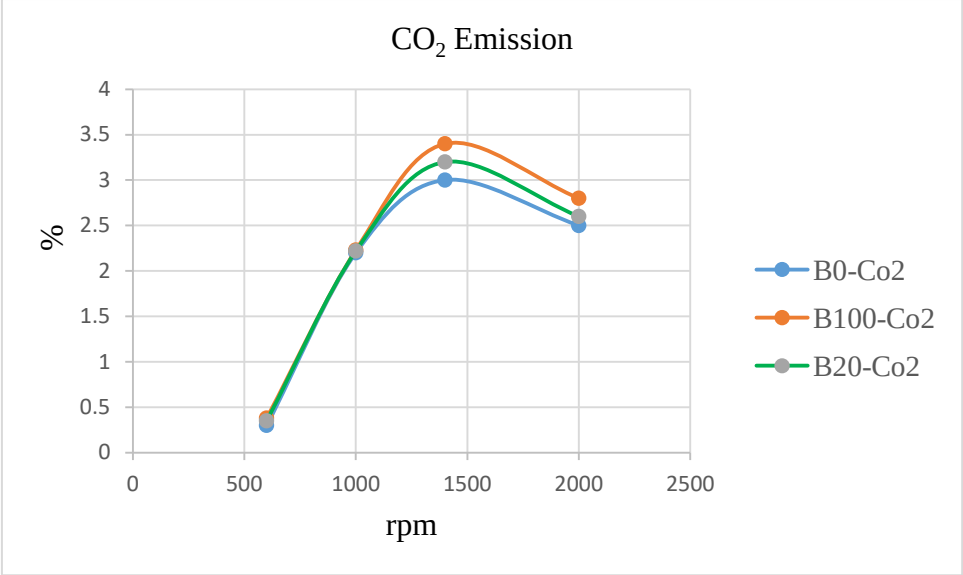


Fig. 39: CO_2 emission characteristics

4.3.3. Hydrocarbon emissions:

The un burnt hydrocarbon emissions are a direct result of incomplete combustion, due to the incomplete mixing of the air and fuel. The concentration of unburned hydrocarbon decreases with engine load. HC emissions for different emulsions were found to be higher than diesel due to the higher density of emulsion fuels, resulting in poor atomization.

Table 31: HC emission data

Engine speed, (rpm)	HC emission (ppm)		
	B0	B100	B20
600	178	180	179
1000	287	290	289
1400	152	160	157
2000	150	165	159

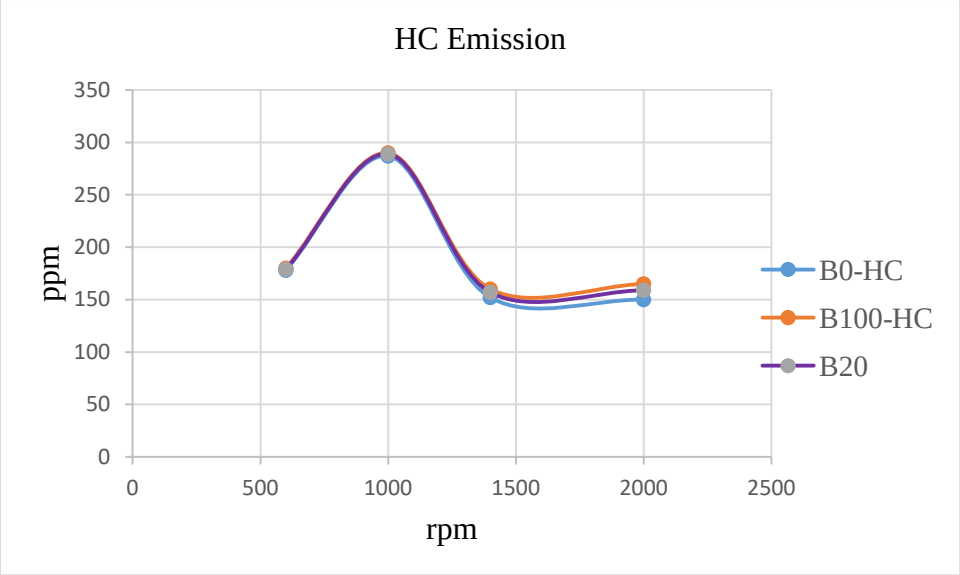


Fig. 40: HC emission characteristics

Table 32: General combined data for emission of B0, B100 and B20.

N (rpm)	Automotive Diesel Oil (B0)				Distilled TPO (B100)				Blended DTPO (B20)			
	NO_x (ppm)	CO (%)	CO_2 (%)	HC (ppm)	NO_x (ppm)	CO (%)	CO_2 (%)	HC (ppm)	NO_x (ppm)	CO (%)	CO_2 (%)	HC (ppm)
600	320	0.06	0.3	178	330	0.08	0.38	180	328	0.07	0.35	179
1000	472	1.02	2.2	287	480	1.03	2.23	290	478	1.02	2.22	289
1400	676	1.04	3	152	690	1.06	3.4	160	550	1.01	3.2	157
2000	501	0.52	2.5	150	530	0.6	2.8	165	502	0.55	2.6	159

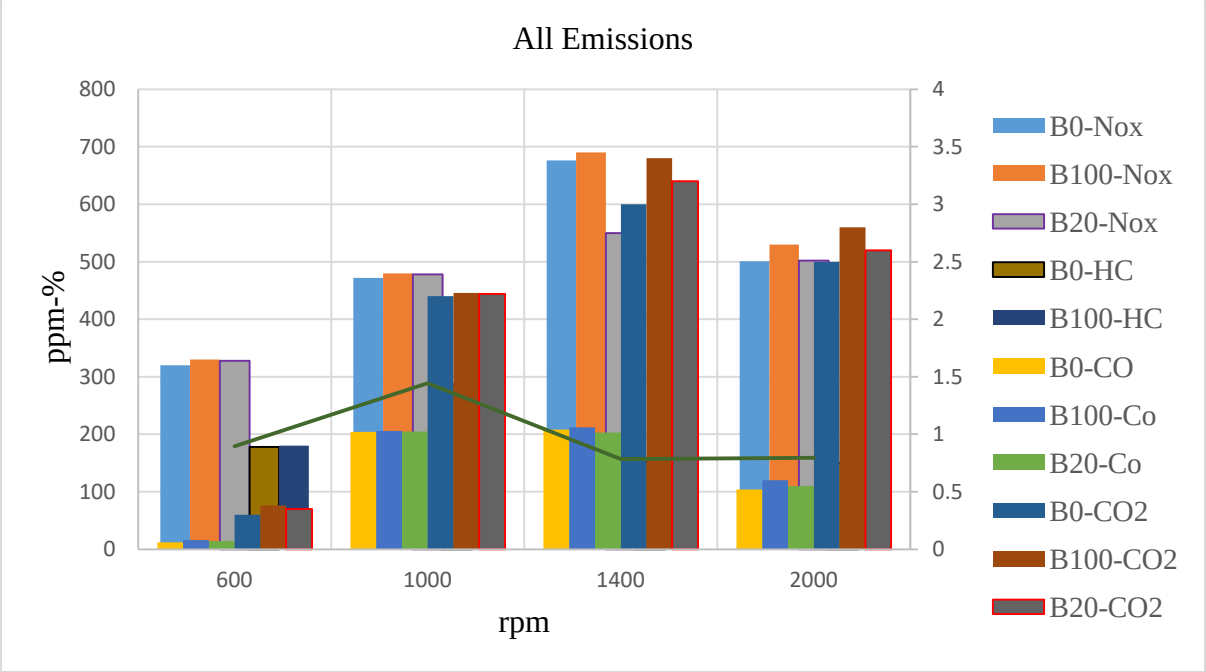


Fig. 41: Over all emission characteristics

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The main ambition of the research is to produce and compare the performance characteristics of diesel produced from waste tyre with that of automotive diesel in the existing four stroke cycle diesel engine without doing amendments. The results from the research are explained as follows.

5.1. Summary

Tires are waste materials that are thrown away after the outfit period life is ended and it is available in tyre station house, vehicle insurance company and some land fields in large amount as a waste, so using the waste tyre for diesel production gives two benefits that is for waste management and production of alternate fuel.

The performance test results describe the tested B100 and blend B20 perform almost similar when compared with the performance of automotive diesel oil (ADO). The torque and power performances get reduced and fuel consumption increase as the percentage of DTPO diesel increase but slightly reduced in DTPO diesel blended

The flash point of waste tyre diesel is 94^0C which is enough higher than the recommended diesel fuel. Therefore, diesel from DTPO is safer to fire hazard during storage and custody transfer of fuel and the copper strip corrosion 3hrs @ 100^0C illustrated much preferable as pure petro diesel fuel which is 1A and this is used for detect the corrosive effects of a lubricant on copper alloys and oil analysis method for gearbox, turbine and hydraulic lubricants.

The overall emission performance results describe the tested B100 and DTPO-B20 fuels are perform almost similar when compared with the performance of ADO. The NO_x, CO, CO_2 and HC emission performances get optimized at the lower engine speed and clearly reduced at the higher engine speed.

5.2. Conclusions

- In this work crude waste tyre oil extracted on small scale was selected for diesel production. It was produced by means of pyrolysis process, which can be described as a renewable energy sources.
- Diesel characterization was done in national petroleum fuels organization (EPSE), and the result of all important properties was performed in each range of the ASTM.

- The engine test was carried out on a chassis dynamometer on 4 stroke diesel engine with neat diesel to take base line, and with B100 and B20 to evaluate the performance characteristics of diesel blend. Performance parameters of the engine with two different diesel fuels were investigated and compared with that of automotive diesel fuel. The brake power was generally slightly lower throughout the engine speed range due to the slightly different in calorific values.
- BSFC for the B100 and automotive diesel fuel was slightly higher but it was less in B20. This is probably because of high calorific values of the distilled diesel DTPO and B0.
- The overall emission performance results describe the tested all fuels are perform a very decent reduction of the emission during running the engine from the lower to upper rpm speed The NO_x, CO & CO_2 emission performances get optimized at the lower engine speed and clearly reduced at the higher engine speed. However, the HC value varies at the upper rpm speed when compared to the others.
- The NOx emissions from waste tyre fuel are less than diesel fuel for all engine speed. This is due to the local Nitrogen amount in the fuel that affects the emission characteristics.

5.3. Recommendations

- The accumulation of waste tires in our field lands are almost fully charged as illegally. Hence I recommend the apprehensive bodies and a government agency has to create awareness on the reduction of illegal accumulation and has to concern on the basis of the advantage of waste tyre.
- In this work from waste tyre around 90% of liquid fuel is produced by using pyrolysis machine mild steel cylindrical reactor up to a maximum temperature of 900^oC is used. These machines were very less in number in our country. So I recommend the government has to launch a waste tyre oil factory.
- Lastly, I recommend the department of mechanical and vehicle engineering of Adama science and technology university to outfit engine dynamometer which is very important to make a research work on renewable energy sources like diesel fuel, gasoline and crude naphthalene fuel from wastes or from different feed stocks so that more reliable result on performance and emission analysis will be obtained.

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