MAJOR PROJECT-II

PRODUCTION AND UTILIZATION OF LIQUID FUEL DERIVED FROM WASTE PLASTIC IN A AGRICULTURE DIESEL ENGINE

Submitted in partial fulfilment of the requirement for the award of degree of

Master of Technology
In
Thermal Energy

Submitted by

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DECLARATION

I, hereby declare that the work which is being presented in this dissertation, titled **“PRODUCTION AND UTILIZATION OF LIQUID FUEL DERIVED FROM WASTE PLASTIC IN AN AGRICULTURE DIESEL ENGINE”** towards the partial fulfilment of the requirements for the award of degree of **Master of Technology** with specialization in THERMAL ENGINEERING from Delhi Technological University Delhi, is an authentic record of my own work carried out under the supervision of **Dr. Naveen Kumar**, Professor, Mechanical Engineering Department, Delhi Technological University, Delhi.

The matter embodied in this dissertation record has not been submitted by me for the award of any other degree.

SUMEET REWALIA

M.Tech (THE)

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CERTIFICATE

This is to certify that the work embodied in the dissertation entitled **“PRODUCTION AND UTILIZATION OF LIQUID FUEL DERIVED FROM WASTE PLASTIC IN A AGRICULTURE DIESEL ENGINE”** by SUMEET REWALIA (2K15/THE/17) in partial fulfilment for the award of degree of Master of Technology in Thermal Engineering, is an authentic record of student’s own work carried out under my guidance and supervision.

It is also certified that the report has not been submitted to any other institute/university for the award of any degree.

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M.Tech (THE)

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ABSTRACT

Waste plastic disposal and excessive use of fossil fuels have caused environment concerns in the world. Both plastics and petroleum derived fuels are hydrocarbons that contain the elements of carbon and hydrogen. The difference between them is that plastic molecules have longer carbon chains than those in LPG, petrol, and diesel fuels. Therefore, it is possible to convert waste plastic into fuels.

The pyrolysis reaction consists of three progressive steps: initiation, propagation, and termination. Initiation reaction cracks the large polymer molecules into free radicals. The free radicals and the molecular species can be further cracked into smaller radicals and molecules during the propagation reactions. At last, the radicals will combine together into stable molecules, which are termination reactions. The activation energy and the energy requirement for the pyrolysis are dependent on the reaction process and the distribution of the final products. Following the equations from the literatures, the theoretical energy requirement to pyrolyze 1kg PE is 1.047 MJ. The measured calorific value of the product obtained is 45.3 MJ/kg. Therefore, the energy profit is very high for this process.

The main objectives of this study were to understand the processes of plastic pyrolysis for maximizing the diesel range products and to test the fuel obtained in an agriculture diesel engine. Pyrolysis of polyethylene (PE) has been investigated experimentally in a lab-scale pyrolysis reactor. The key factors have been investigated and identified. A batch reactor type pyrolysis reactor is designed and liquid fuel is obtained from the waste plastic particularly. Feed Material used is low density polyethylene that is generally polythene bags and plastic cups. The performance and emission characteristic of agriculture engine is also investigated running on plastic pyrolysis oil and compared it with diesel fuel.

The plastic was cracked thermally at temperature range of 500ºC to 600ºC. The products obtained were of different composition and the product yield was different for different temperatures. The liquid product obtained had a specific gravity of 0.7787, kinematic viscosity of 1.6 and calorific value of 45.3 MJ, which is quite good and falls in the range of diesel fuel. These properties do also match with the gasoline range fuels but the flash point is very high. Thus the plastic pyrolysis oil was tested only in the diesel engine.

The engine was able to operate stably on plastic pyrolysis oil at different engine rpm and load. The engine brake thermal efficiency was lower for 100 % plastic pyrolysis oil comparison to diesel. All measured emissions (NOx, UHC, CO and CO2) were higher for plastic pyrolysis oil compared to diesel, however if we use blends of plastic pyrolysis oil and diesel then emissions could be controlled.

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NOMENCLATURE

1	PPO	Plastic Pyrolysis oil
2	WPO	Waste Plastic oil
3	NO_x	Nitrogen oxides
4	PM	Particulate matter
5	CO	Carbon monoxide
6	CO_2	Carbon dioxide
7	HC	Hydrocarbon
8	BTE	Brake thermal efficiency
9	BSFC	Brake specific fuel consumption
10	BMEP	Brake mean effective pressure
11	LHV	Lower heating value
12	PPO 100	100 % plastic pyrolysis oil
13	LDPE	Low density polyethylene
14	HDPE	High density polyethylene
15	HRR	Heat release rate

1. Introduction

1.1 PLASTICS

Plastic was invented by A.Parkes in 1862. Plastic is a polymer having high molecular weight. Polymers are formed as a result of polymerisation reaction in which monomers react in presence of catalyst to give long chain of polymers. For eg. Monomer of styrene will lead to formation of polystyrene and its structure is shown below:

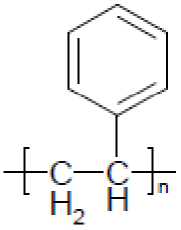

Figure1.1: Polymer of styrene

The repetitive unit of the polymer is enclosed within the brackets and subscript n denotes it. n is representative for the number of units contained in the polymer molecule. Plastic is very commonly used and is classified on the basis of its chemical structure, process of synthetization, density etc. Society of Plastic Industry (SPI) assist in recycling of waste plastic as they have a well-defined identification code system for resins that categorizes plastics into following mentioned seven groups according to their applications and its chemical structure:

Subscript n outside the brackets indicates number of units repeated in the polymer molecule. Plastic is widely used and very common in day to day life and is categorised on the basis of chemical structure, density and process by which it is synthesized etc. waste plastic recycling is facilitated by SPI ie. Society of Plastic Industry which have a defined code system for resin identification which is catagorised into seven groups according to its usage and physio-chemical structure.

PET (Polyethylene Terphthalate).
PVC (Polyvinyl Chloride).
PS (Polystyrene).
LDPE (Low Density Polyethylne).
HDPE (High Density Polyethylne).
PP (Polypropylne).

The following are seven types of plastics marked on different kinds of plastic products:

Fig 1.2: Symbols of different plastics on various products.

The ease of production and applications of plastic worldwide has increased from 1.5 million ton to 260 million ton since 1950 to 2007. And now the major concern has become its disposal.

1.2 TYPES OF PLASTIC

Plastic classification has been done on the basis of polymer molecules structural shape either linear, branched, or cross linked, as specified in the figure 1.1.

In linear polymers, units are attached end to end and in branched it can lead to branches in the main polymer chain. If repetition of side groups are regular then it will not be considered as branches of polymer chain. The above example of the polystyrene is a linear polymer though functional groups are present as a part of monomer structure. However in case of branch polymerization, one of the monomers should be attached to more than two functional groups. Branched structure and side functional group play an important role on the product obtained by the pyrolysis.

For instance, the dominating component of pyrolysis of polystyrene is styrene that comes from the side group of Polystyrene backbone.

A remarkable relationship is observed between density and intensity of branching among polymers. More the number of branches in Polyethylene the lower will be the density. Therefore, branched polyethylene can be known as low density polyethylene (LDPE), which differs from linear polyethylene known as high density polyethylene (HDPE).

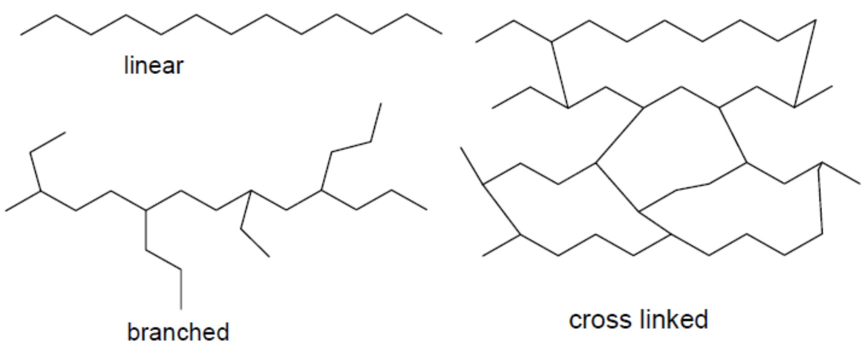

Fig 1.3 Different polymer structures

TYPE	RECYCLABLE	ABBREVIATION	DESCRIPTION
Type-1	YES	PET	Polyethylene Terephthalate Beverages
Type-2	YES	HDPE	Milk bags, detergent & oil bottles, plastic toys, containers used outside, parts and plastic bags

Type-3	YES,	V/PVC	Vinyl chloride Food wrapers, vegetable oil bags, blister packagings or different automotive parts.
Type-4	YES	LDPE	Low density polyethylenes, different plastic bags, shrink-wraps, garment bags or containers
Type-5	YES	PP	Poly propylene, refrigerated containers, some bags, most bottle tops, some carpets
Type-6	YES, BUT NOT COMMON	PS	Polystyrenes, through away utensils, meatpacking, protective packing
Type-7	SOME	------	Other usually layered or mixed plastic

Table 1.1: Types of waste plastics and their recyclables [10]

1.3 WASTE PLASTIC DISPOSAL PROBLEM

According to the survey that was conducted nation wise, in the year 2005, approximately 12,000 tons of plastic waste were generated each day in our country, and around only 60% of the waste was recycled, and rest was made to dispose of. So gradually it goes on accumulating, thereby leading to serious disposal problems. [1]. Plastic is for the most part gotten from various petrochemical resources. These plastics are for the most part solidified oil. They along these lines have regularly high calorific energy value.

Plastics belong to polymer category which is non-biodegradable. They generally contain carbon and hydrogen, and couple of different components. As plastics are non-biodegradable in nature the waste created from waste plastic contributes intensely to the issue of city waste administration. Plastic generation is expanding altogether. Currently, 200MT plastic waste is produced worldwide [2]. The utilization of plastic in most recent couple of decades is expanding quickly. Below given table demonstrates the scenario of utilization of the plastics in a portion of the chose nations overall [8].

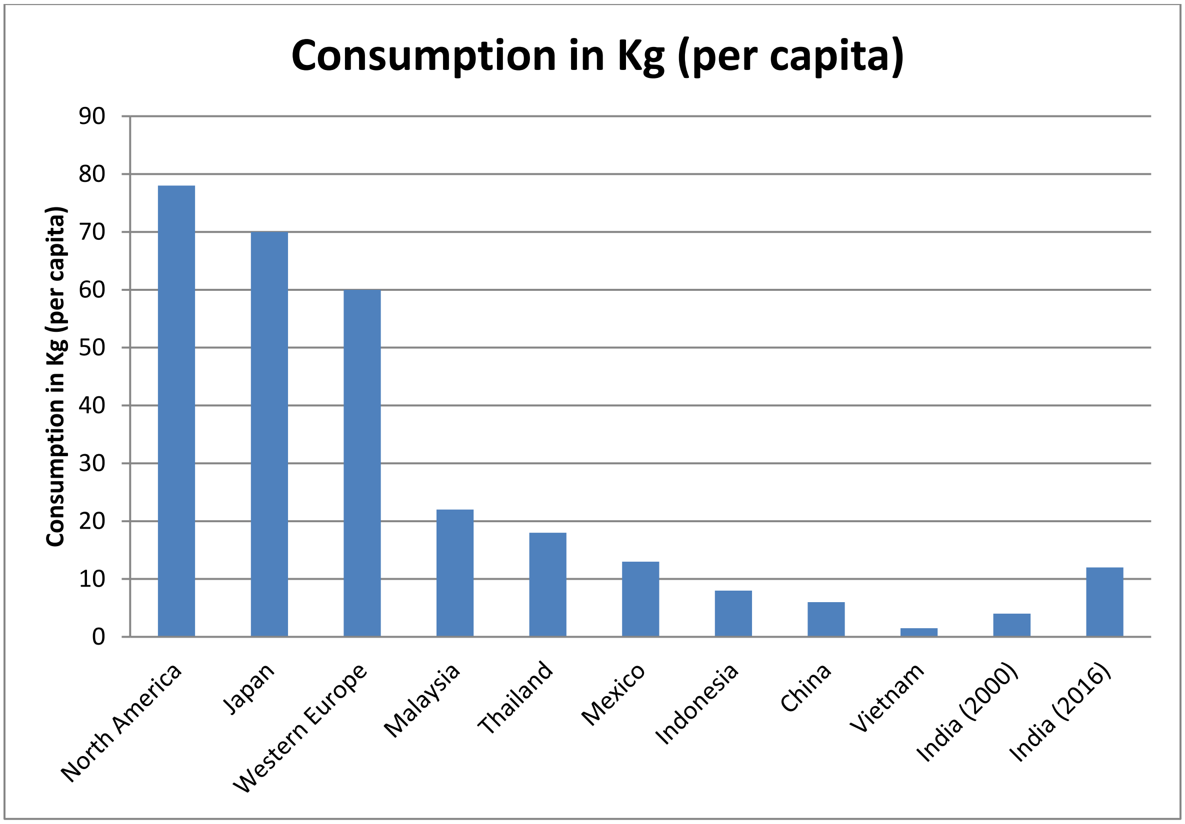

Fig 1.4: Consumption of Plastics in Some of the Selected Countries of the World.

In the coming near future the world will be going to face problems with respect to the energy and environmental concerns because of the over consumption of the fossil fuels and the energy. We need to find some alternate solutions to the problem that may promote the sustainable growth to tackle the situation. One such aspect can be processing of renewable sources of energy or energy extraction from the waste streams. Regarding pyrolysis of plastic, one can easily say that it is an economical method to tackle the problem of waste plastic management and also it will produce the quality liquid fuel which, as concluded in the thesis, has very similar physio-chemical properties compare to the petroleum fuels such as diesel.

When data was collected for 60 major cities it was found that over 3,500 tons of waste plastics was generated on everyday basis. Environment Minister Prakash Javadekar also informed that in

2013-14, plastic consumption in our country was about 11 million tons. The major contribution is from the cities of Delhi, Chennai, Bengaluru, Mumbai, Kolkata, Ahmedabad and Hyderabad," he informed during questionnaire session. In recent years, many committees investigated the adverse impact of plastic on environment. The committee's reports are the indication that if systematic collection of plastic bags are not performed systematically then it lead to choking of drainage system and cause disease due to insanitary conditions. Discarded foods littered around dustbins contains plastic bags which are ingested by the animals that leads to choking of their food pipe and can cause their death. Plastic waste thrown on soil reduces the recharging capacity of the ground aquifers, plastic packed items and containers also leads to contamination, said by Javadekar.

1.4 THE PYROLYSIS OF PLASTIC MATERIALS

Pyrolysis refers to breakdown of the polymer having ample atomic weight of carbon chains in the absenteeism of oxygen condition and delivers little sub-atomic weight particles. Conventional ways for post-devoured plastics were landfills or burning.

In any case, landfill of the post-devoured plastics has potential issues due to constrained land asset and high solidness of plastics. Fragmented burning may produce noxious substances and causes genuine medical issues. High Density PolyEthene, Low Density PolyEthene, PolyPropylene and PolyStyrene are few examples of polymers consisting of carbon and hydrogen, for instance, condensed oil gas (LPG), diesel and petrol. Plastics are produced from oil and has calorific value in a similar range as that of LPG, petrol and diesel as given in Table 1.2.

Material	**Calorific Value**
Polyethylene	46.3
Polypropylene	46.4
Polystyrene	41.4

Polyvinyl Chloride	18.0
Coal	24.3
Liquefied petroleum gas	46.1
Petrol	44.0
Heavy fuel oil	41.2
Kerosene	43.0
Light fuel oil	41.8
Diesel	43.5

Table 1.2- Energy density of plastic and some fuels

Few plastic pyrolysis plants are operational that acknowledges a wide variety of post consumed plastics by the utilization of hydrochloride scrubber, for splitting of the PVC that may not be the ideal in the fuel as chloride s not attracted in the fills. The above plants utilizing these techniques are modern and thus not reasonable for small scale creation. These plants uses catalyst which enhances the characteristics of pyrolysis items used in various equipments. Few hardware’s have some limitations when it comes to longer resistant time of materials, disagreeable contact between catalyst and plastic, it may also need higher exchange of heat rate as well as cost setup. One should keep an end goal in the mind in order to understand as well as reform the pyrolysis process and to study about its effects on the various varieties of plastics. Influence of the response conditions of the pyrolysis item were examined by Kaminsky, Scheirs. Williams concentrated the products of pyrolysis from individual as well as blended plastics. Aguado tried to explore the effect of catalyst on the responses of pyrolysis. In these reviews, the lab-scale pyrolysis reactors were cluster sort or semi-bunch sort as opposed to ceaseless sort.

The effects of operating temperature, rate of heating and catalytic yield attracted most of the reviews. However, there may be further investigation regarding the examination of procedure related to cracking of the complex pyrolysis products. However, the end products are very confusing. There are more than hundred segments in various hydrocarbons that may be olefin, paraffin or t can be their isomers. Frequently, PONA framework is utilized to determine oil hydrocarbons including paraffin, olefin, naphthalene and aromatic, which stands for PONA. Paraffins are saturated hydrocarbons with only single bonds between carbon chains of hydrocarbons and are also coined as “alkanes”. Olefins are unsaturated hydrocarbons which contains either one double bond or triple bonds between carbon chains of hydrocarbon and are termed as “alkenes” and “alkynes”. Napthalenes are aromatic compounds containing carbon chains to form ring like structure and that structure is known as benzene ring. Another method to understand hydrocarbons is on the basis of number of carbon atoms in their structure. That is a connection to oil powers. Oil gases, oil, diesel, lamp oil and wax are few of the pyrolysis items which are unpredictable by weight. Table1.3 shows hydrocarbon range in commercial fuels. There are many different approaches depicting the hydrocarbons, for instance, boiling point, physical state of the products at room temperature.

Fuels	LPG	Petrol	Kerosene	Diesel	Heavy fuel oil
Hydrocarbons	C_3 to C_4	C_4 to C_{12}	C_{12} to C_{15}	C_{12} to C_{24}	C_{12} to C_{70}

Table 1.3 Hydrocarbon range in commercial fuels

1.5 ECONOMIC VALUE OF THE PROCESS

The innovation helps us to save assets by using waste plastics to create important valuable energy. Presently, a major share of the waste plastic is land filled and it is not economical on the grounds that waste plastic take long time to get deacayed. The world's yearly utilization of plastic which was five million tons in the 1950's has soar to a worldwide creation of 245 million tons in 2008 and waste plastic era is quickly expanding. Plastic waste is the third biggest supporter of city and modern waste frameworks after food and paper.

Accordingly, critical measure of vitality can be delivered with this innovation. This could be an optional energy source for substituting petroleum products. The fuel created from this procedure doesn’t contain sulfur content in light of the fact that there is no sulfur in the waste plastic feedstock. This is favorable position contrasted and the great petroleum derivatives, for example, diesel since sulfur content in the fills could shape SO2 after burning. SO2 is a toxin creating serious air contaminations, which influences individuals well-being and harms the solid structure.

Thus, this innovation is environmental friendly and has huge positive effect on the government and community.

1.6 ENERGY CRISIS

Energy is the key parameter of remarkable economic growth and essential to the existence of current economy. Long-term accessibility of energy is the indicator of economic growth and dependent on the sources which are easily available and environmental friendly. Global warming, acid rain and ozone layer depletion have become serious problem in past few decades. To reduce these unwanted environmental effects, some rigorous actions have been taken in terms of worldwide protocols and conventions. There is much need of huge investments to fulfill the energy demand especially in case of developing countries because energy sector has become the crucial parameter for development of any country. The IC engine have bestowed the world with industrialization but also promoted the cause of environmental degradation. There are lot of conventions are going on to produce non-conventional source of energy to beat the energy crisis as soon as possible.

High efficiency and rough use of diesel engine played a very important role in Indian economy because they are used in agriculture, power, industry and transport sector. Environmental pollution and harmful emissions from CI engines raised the point to protect the environment globally. The concern for saving of diesel too leads the necessity of alternative fuel which equalizes the property of diesel to meet the same results.

1.7. OBJECTIVES OF THE PRESENT STUDY

The true objective of this study was to design a continuous pyrolysis apparatus and produce the liquid fuel from the waste plastic particularly. Material to be used is low density polyethylene that are generally polythene bags and plastic cups. The performance and emission characteristic of agriculture engine is also investigated running on plastic pyrolysis oil and comparing it with diesel fuel.

Chapter 2

LITERATURE REVIEW

For the purpose to set the target of present research and also to justify it properly, the available literatures have been critically reviewed. The literature review is presented in this chapter classifying them into two broad categories as follows:

1) Review pertaining to production of plastic pyrolysis oil and different parameters, techniques.

2) Review pertaining to Performance and emissions of an diesel engine operated on plastic oil (PPO).

2.1 Review Pertaining to production of plastic pyrolysis oil

Venkateshan et al. has provided concise summary of plastic pyrolysis for each type and a discussion of the main affecting parameters to optimize liquid oil yield. Based on the studies on literatures, pyrolysis process was chosen by most researchers because of its potential to convert the most energy from plastic waste to valuable liquid oil, gaseous and char. Therefore, it is the best alternative for plastic waste conversion and also economical in terms of operation. The flexibility that it provides in terms of product preference could be achieved by adjusting the parameters accordingly. The pyrolysis could be done in both thermal and catalytic process. However, the catalytic process provided lower operating temperature with greater yield of liquid oil for most plastics with the right catalyst selection. The sustainability of the process is unquestionable since the amount of plastic wastes available in every country is reaching millions of tons. With the pyrolysis method, the waste management becomes more efficient, less capacity of landfill needed, less pollution and also cost effective. Moreover, with the existence of pyrolysis method to decompose plastic into valuable energy fuel, the dependence on fossil fuel as the non-renewable energy can be reduced and this solves the rise in energy demand. [1]

Navarro et al. showed the successful application of the distributed activation energy model to study the effects of dynamic experiments on pyrolysis of ABS plastic, tyre rubber, coal and wood by fitting two sets of data obtained in thermo gravimetric experiments with different heating rates. It is the first time that DAEM is applied to ABS devolatilisation and a relatively homogeneous distribution of activation energies with mass allocated in an only main reaction was observed. Tyre rubber was also studied for the first time by a DAEM algorithm and showed a maximum activation energies for low fraction of mass remaining and a wide distribution of the mass all over the reactions, with reactions related to main components N, SBR and BR. The main kinetic parameters were used in the DAEM algorithm successfully implemented with a particle heat transfer model in order to predict the thermal behaviour of solid fuels. The effect of several process variables such as particle size, inlet feedstock temperature, reactor temperature and global heat transfer coefficient, has been studied. The most influencing variable showed to be the particle size followed by the reactor temperature needed to fulfil the devolatilisation of the sample. The intrinsic devolatilisation characteristics, like the more gradual weight lost and the higher starting temperature, strongly affect the conversion time needed to reach conversions of 90%. In addition, it can be concluded that the use of different feedstock in established treatments can be previously studied with theoretical models in order to fix in advance ranges of optimal process conditions or to know approximations to the treatment potential. [2]

Hartulistiyoso et al. aimed to study temperature distribution in the pyrolysis process of waste plastic bottles as drinking water packages (PET), which are immensely available in Indonesia. This research used lab-scale reactor experiment to analyze temperature distribution in the reactor. The simulation of Computational Fluid Dynamic (CFD) was also used in this research to know the temperature contour inside the reactor. [3]

D. Damodharan at al. extracted waste plastic oil (WPO) from mixed waste plastic by catalytic pyrolysis and its chemical composition was characterized by using GC/MS. Later, this study sets out to investigate the effects of n-butanol addition to WPO/diesel blends in a single cylinder, direct injection diesel engine. Three ternary blends (D50- WPO40-B10, D50-WPO30-B20 and D50-WPO20-B30) were prepared and the effect of n-butanol addition on performance and emission characteristics of a DI diesel engine was then compared with diesel and WPO for any improvements. The following conclusions were drawn from the investigation,

1. WPO could be extracted from mixed waste plastic by pyrolysis using ZSM-2 as a catalyst. The properties of WPO determined using ASTM methods, were found to be closer to diesel and can be used in its neat form in a diesel engine without modifications. GC/MS characterization revealed that WPO consists of 15 chemical compounds with heavy hydrocarbon chains varying from C13 to C22. The aromatic content was found to be 39%.
2. BTE of the engine increased with increasing n-butanol fraction in the blends when compared to WPO. D50-WPO40-B10 and D50-WPO30-B20 blends delivered better performance than WPO. BTE of D50-WPO20-B30 was found to be even better than baseline diesel operation. 3. BSFC of the ternary blends was higher than ULSD due to its lower energy content. However the blends presented lower BSFC when compared to WPO. Ternary blends burned leaner when compared to WPO in the engine.
3. Smoke opacity decreased with increasing n-butanol fraction in the blends. Smoke opacity reduced favorably for D50-WPO40- B10, D50-WPO30-B20 and D50-WPO20-B30 when compared to both WPO and diesel.
4. Addition of 10% n-butanol by vol. to WPO/ULSD blend (D50- WPO40-B10) reduced NOx emissions favorably when compared to both WPO and diesel. However NOx emissions were higher than the corresponding WPO case for higher volume nbutanol blends (D50-WPO30-B20 and D50-WPO20-B30).6. HC emissions are generally high for WPO when compared to diesel. HC emission increased with increasing n-butanol content in the blends. CO emissions remained unchanged for all WPO/ULSD blends after the addition of n-butanol. 7. Low volume addition of n-butanol (10% by vol.) to WPO/diesel blends presented less NOx, smoke emissions with improvement in engine performance when compared to diesel. In summary, n-butanol was found to be favorable in terms of emission and performance of WPO and its addition could be an advantageous strategy to improve the utilization of both a recycled component (WPO) and a renewable bio-component (n-butanol). [4]

Sachin Kumar et al. studied performance and emission analysis of blends of waste plastic oil obtained by catalytic pyrolysis of waste HDPE with diesel in a CI engine. Compression ignition engines have proved to be the best option in heavy duty applications like transportation and power generation, but rapid depleting sources of conventional fossil fuels, their rising prices and ever increasing environmental issues are the major concerns. The present study deals with performance and emission analysis of blends of waste plastic oil obtained by catalytic pyrolysis of waste high-density polyethylene with diesel in a CI engine with varying loads. The experimental results show that the brake thermal efficiencies at all load conditions are lower as compared to that of diesel fuel, exhaust gas temperature increases with increase in engine load. The BSFC increases with increase in WPO blend ratio and decreases with increase in engine load. Mechanical efficiency increases with increasing brake power for all fuel blends. The NOx emission and CO emission increase with increase in percentage of waste plastic oil in blends, NOx emission decreases while CO emission increases with increase in engine load. The unburnt hydrocarbon emission decreases with increase in the engine load and increases with increase in percentage of waste plastic oil in blends. The carbon dioxide emission for the blends is lower than diesel for almost all loads and all blends. [5]

Areeprasert et al. performed the pyrolysis of waste plastic based on the characterization of municipal plastic waste (MPW) from one of Bangkok city’s waste transfer station. Results showed that heating value of oil product (49, 47, 43, and 42 MJ/kg, from LDPE, mixture of HDPE and LDPE, PP and HDPE, respectively) was significantly higher than that of the raw plastic waste. Yield of the oil product from the pyrolysis of LDPE was highest (60%). Energy recovery from plastic via pyrolysis was 75%, 59%, 50%, and 49% for LDPE, mixture of HDPE and LDPE, PP, and HDPE, respectively. Results from GC-MS of pyrolysis oil showed that different raw materials produced very different sets of chemical compounds, with alkanes and alkenes found in the pyrolysis oil. [6]

Syamsiro et al. aimed his research to study fuel oil production from municipal plastic wastes by sequential pyrolysis and catalytic reforming processes. Three kinds of municipal plastic wastes were collected from the final disposal site and the small recycling company in Yogyakarta city, Indonesia. Commercial Y-zeolite and natural zeolite catalysts were used in this study. The results show that the feedstock types strongly affect the product yields and the quality of liquid and solid products. HDPE waste produced the highest liquid fraction. The catalyst presences reduced the liquid fraction and increased the gaseous fraction. Furthermore, municipal plastic wastes pyrolysis produced higher heating value solid products than those of biomass and low rank coal.[7]

Xue at al. studied effect of catalyst contact mode and gas atmosphere during catalytic pyrolysis of waste plastics. In the present study, polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET) were pyrolyzed using HZSM-5 zeolite in a tandem micro-pyrolyzer to investigate the effects of plastic type, catalyst and feedstock contact mode, as well as the type of carrier gas on product distribution. Among the four plastics, PS produced highest aromatic yields up to 85% whereas PE and PP mainly produced aliphatic hydrocarbons. In comparison to ex-situ pyrolysis, in-situ pyrolysis of the plastics produced more solid residue but also promoted the formation of aromatic hydrocarbons, except PS. For PS, ex-situ pyrolysis produced a higher yield of aromatics than in-situ pyrolysis, mostly contributed by high styrene yield. During in-situ pyrolysis, the catalyst reduced the decomposition temperatures of the plastics in the order of PE, PP, PS and PET from high to low. Hydrogen carrier gas reduced solid residue and also increased the selectivity of single ring aromatics in comparison to inert pyrolysis. Hydrogen was more beneficial to PS and PET than PE and PP in terms of reducing coke yield and increasing hydrocarbon yield. The present study also showed that catalytically co-pyrolyzing PS and PE, or PET and PE increases the yield of aromatics and reduces the yield of solid residue due to hydrogen transfer from PE to PS or PET and alkylation reactions among the plastic-derivatives. [8]

Ratnasari et al. investigated the two-stage pyrolysis-catalysis of high density polyethylene with pyrolysis of the plastic in the first stage followed by catalysis of the evolved hydrocarbon pyrolysis gases in the second stage using solid acid catalysts to produce gasoline range hydrocarbon oil (C8–C12). The catalytic process involved staged catalysis, where a mesoporous catalyst was layered on top of a microporous catalyst with the aim of maximising the conversion of the waste plastic to gasoline range hydrocarbons.

The catalysts used were mesoporous MCM-41 followed by microporous ZSM-5, and different MCM- 41:zeolite ZSM-5 catalyst ratios were investigated. The MCM-41 and zeolite ZSM-5 were also used alone for comparison. The results showed that using the staged catalysis a high yield of oil product (83.15 wt.%) was obtained from high density polyethylene at a MCM-41:ZSM-5 ratio of 1:1 in the staged pyrolysiscatalysis process. The main gases produced were C2 (mainly ethene), C3 (mainly propene), and C4 (mainly butene and butadiene) gases. In addition, the oil product was highly aromatic (95.85 wt.% of oil) consisting of 97.72 wt.% of gasoline range hydrocarbons. In addition, pyrolysis-staged catalysis using a 1:1 ratio of MCM-41: zeolite ZSM-5 was investigated for the pyrolysis–catalysis of several real-world waste plastic samples from various industrial sectors. The real world samples were, agricultural waste plastics, building reconstruction plastics, mineral water container plastics and household food packaging waste plastics. The results showed that effective conversion of the real-world waste plastics could be achieved with significant concentrations of gasoline range hydrocarbons obtained. [9]

Muhammad et al. collected plastic waste from waste electrical and electronic equipment (WEEE) and pyrolysed in the presence of zeolite catalysts to produce a gasoline range aromatic oil. The plastic was from equipment containing cathode ray tubes (CRTs) and also plastic waste from refrigeration equipment. In addition, for comparison the main plastics contained in the WEEE, in the form of high impact polystyrene (HIPS) and acrylonitrile-butadiene-styrene (ABS) were also pyrolysed in the presence of the zeolite catalysts. Two zeolite catalysts; Y zeolite and ZSM-5 were used. Catalytic pyrolysis took place in a two stage fixed bed, batch reactor with the plastic pyrolysed in the first stage and the evolved pyrolysis gases catalysed in the second stage reactor. The quantity of oil produced from uncatalysed pyrolysis of plastics from CRTs and refrigerators was more than 80 wt%. The gases consisted of hydrogen, methane and C2–C4 hydrocarbons. When the zeolite catalysts were introduced there was a decrease of between 5 and 10 wt% in oil yield and a corresponding increase in gas yield. The composition of the oils derived from the uncatalysed pyrolysis of WEEE plastics were mainly aromatic with high concentrations of styrene, derived from the HIPS and ABS present in the plastic waste. Addition of the zeolite ZSM-5 and Y zeolite to the pyrolysis process resulted in significant concentrations of benzene, toluene and ethylbenzene in the product oil but reduced concentrations of styrene.

The oils from both thermal and catalysed pyrolysis also contained significant concentrations of polycyclic aromatic hydrocarbons for example, naphthalene, phenanthrene and pyrene. [10]

Wallis et al. investigated the product yield, composition, and hydrocarbon distribution of gaseous components from the pyrolysis of MPW was investigated in a batch type fixed bed reactor in a temperature range of 450–600 _C. A high yield of gaseous component obtained at higher temperature with decrease in char and increment of wax component in oil product. Gas generation was analysed by time dependent pressure analysis of the process. The main gases obtained were alkenes consisting of methane, ethane, propane & n-butane. Other gases such as H2, CO, & CO_2 were also investigated. The yield and composition of gaseous product obtained from pyrolysis was compared with those obtained from the results based on literature. [11]

The composition of waste plays a very important role in the distribution and quality of the pyrolyzed products such as the high presence of PET increases the CO and CO2 concentration in product gases. Degradation of PET produces CO and CO_2 in early stage of
pyrolysis due to low degradation temperature in respect to other components. In addition, it was found that on increasing the temperature the cracking reduces due to lack of residence of time in reactor and high molecular chain compounds and aromatics were obtained in form of wax in oil product. It was concluded that the residence time of volatiles plays a vital role in formation of lighter hydrocarbons whereas the increase in operating temperature enhances the production of H_2 gas. In a large scale setup plant the amount of gas generated was enormous having high heating value and have a great potential in terms of energy and product recovery as the gases obtained can be utilized for electricity generation by utilizing in steam turbines or can be used in the process itself to cut down the energy inputs for the process and providing a sustainable process with permissible or no pollution.

Mani et al. stated that with growing global energy demands, recovering energy from waste plastic presents an attractive avenue to explore as it promotes recycling. Oil synthesized from waste plastic can be excellent fuel for diesel engines but yields higher carcinogenic smoke emissions and poor performance than fossil diesel (D). His study demonstrates the extraction and characterization of waste plastic oil (WPO) obtained by pyrolysis in a laboratory scale batch reactor and later sets out to investigate the effects of adding a renewable oxygenated component in the form of n-butanol (B), a naturally occurring biofuel. Three ternary blends, D50-WPO40-B10, D50-WPO30-B20 and D50-WCO20-B30 were strategically prepared to utilize both a recycled component (WPO by up to 40%) and a renewable component (n-butanol by up to 30%). The performance and emissions of DI diesel engine when fueled with these blends was then analyzed in comparison with both neat WPO and diesel operation. Results indicated that n-butanol addition presented lower smoke emissions and higher HC emissions when compared to diesel. Addition of 10% n-butanol by vol. to WPO/ULSD blend reduced NOx emissions favorably when compared to both WPO and diesel. However NOx emissions were higher than the corresponding WPO case for higher volume n-butanol blends. Brake thermal efficiency (BTE) of the engine increased with increasing n-butanol fraction in the blends when compared to WPO. Fuel consumption of ternary blends was found to be better than WPO. D50- WPO40-B10 blend presented less NOx and smoke emissions with improvement in engine performance when compared to diesel. Study revealed that n-butanol could be a viable additive for diesel engines operating with WPO extracted from mixed waste plastic. [12]

Lin et al. stated that ZSM-5 zeolite is an efficient catalyst for both biomass deoxygenation and polyolefins cracking in pyrol-ysis process. In this study, wood–plastic composite (WPC), composed mainly of woody materials andthermoplastic polymers, was pyrolyzed using Py-GC/MS over phosphorus-modified HZSM-5 (P-HZSM-5) with varying P loadings (from 0 to 10 wt.%). The catalysts were prepared by wet impregnation methodand characterized by XRF, XRD and NH3-TPD. The effects of pyrolysis temperature, time, heating rate,catalyst to WPC ratio and P loadings on the hydrocarbon distribution of WPC pyrolysis were studied.Pyrolysis conditions have significant effects on hydrocarbon distribution. Parent HZSM-5 facilitated aro-matics formation, while P-HZSM-5 favored the formation of light aliphatic hydrocarbons (C4-C12). Theyields of C4-C12increased first with rising pyrolysis temperature from 450 to 550◦C, then decreased over550◦C. Similarly, C4-C12yields increased during the pyrolysis time from 15 to 30 s and decreased with thefurther prolonged time. A low heating rate (0.002◦C/ms) favored the formation of light aliphatic hydro-carbons, while high heating rates (>0.2◦C/ms) favored the formation of aromatics. Increasing catalyst toWPC ratio augmented aromatic selectivity. Hydrocarbon distribution strongly depended on the catalyst'sacidity, adjusted by varying P loading in P-HZSM-5. The highest yield of C4-C12was obtained while usingP-HZSM-5 with P loading of 3.5 wt.%. [13]

2.1.1 Factors affecting Plastic pyrolysis

The major factors influencing the plastic pyrolysis process and pyrolysis product molecular distribution include chemical composition of the feedstock, cracking temperature and heating rate, operation pressure, reactor type, residence time and application of catalyst. These factors are summarized in this section as follows.

2.1.2. Chemical composition of feedstock

The pyrolysis products are directly related to the chemical composition and chemical structure of the plastics to be pyrolyzed. In addition, the chemical composition of the feedstock also affects the pyrolysis processes. In reality, waste plastics are possibly contaminated before recycling which could also have effects on the pyrolysis process and products.[14]

As mentioned in Chapter 1, PE, PP and PS are most commonly used polymeric hydrocarbons and were selected as the investigated materials in this study. Polyethylene is formed from ethylene through chain polymerization which is shown in Formula 2-1.

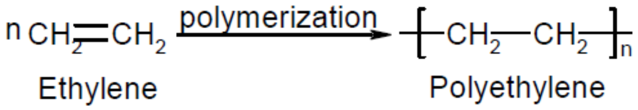

Fig 2.1 Polymerization of ethylene to polyethylene[15]

Plastics can be classified, according to structural shape of polymer molecules, as linear, branched, or cross-linked in Figure 2-1. The units in linear polymer are linked only to two others, one to each ends. The polymer is termed branched when branches extend beyond the main polymer chain randomly. Regularly repeating of side groups are considered to be part of the unit but not considered as branches. Based on the above description, polystyrene is called linear polymer although it contains functional groups as part of the monomer structure. In branched polymers, at least one of the monomers is connected to more than two functional groups due to the branching points produced from the polymerization process. The functional side group and the branch structure have significant effects on the pyrolysis product. For example, the dominant component in PS pyrolysis products is styrene that is the side group come off from PS carbon backbone.

There is a significant relationship between the density and the branching intensity of polymers. The PE with more branches has relatively lower density. This has been found in McMurry's study. **The branched polyethylene is also called low density polyethylene (LDPE), which is different from linear polyethylene that is called high density polyethylene (HDPE)**. [16]

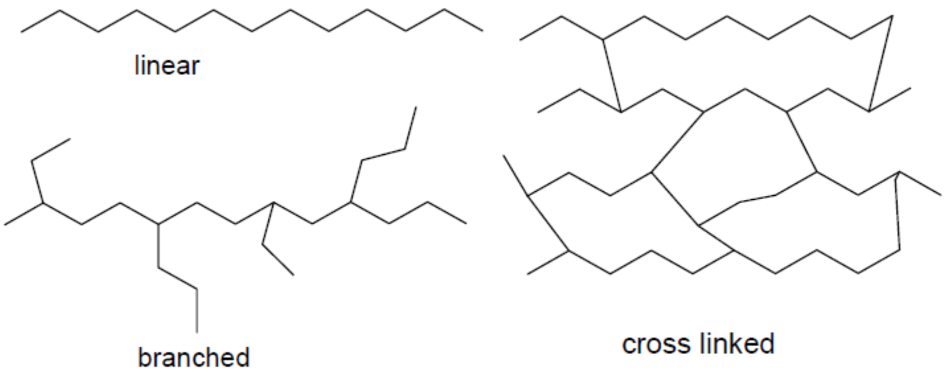

Figure 2.1 Polymer structure, linear, branched and cross linked [17]

A cross linked polymer can be described as an interconnected branched polymer with all polymer chains are linked to form a large molecule. Thus, the cross linked polymer constitutes large molecule. Theoretically, the molecular weight of a cross linked polymer can be infinite. In reality, the molecular weight of a cross linked polymer will be limited due to breaking down of the molecular inter-connections during the processing or the weight of the polymer sample. The cross linked polymer cannot be dissolved in solvents or be melted by heat because of their network structure. For example, PEX, a common abbreviate of cross-linked polyethylene, is widely used in oil and water piping. In pyrolysis process, cross linked polymer will crack rather than melt or evaporate. This is different from the reactions of linear or branched polymers in pyrolysis process.

2.1.3. Cracking temperature and heating rate

Temperature is one of the most important operating variable, since the temperature dominates the cracking reaction of the polymer materials. Not all of the polymer materials can be cracked by increasing the temperature. **Van der Waals force** is the force between the molecules, which attracts molecules together and prevents the collapse of molecules.[18] When the vibration of molecules is great enough, the molecules will evaporate from the surface of the object. However, the carbon chain will be broken if energy induced by van der Waals force along the polymer chains is greater than the enthalpy of the C-C bond in the chain. This is the reason why high molecular weight polymer is decomposed rather than is boiled when it is heated. In theory, the temperature of thermal breaking the C-C bonds should be constant for a given type of plastic (polymer). However, this temperature has been found to differ in different studies. For example, the temperature when PP starts cracking was reported at 380 ºC in Ciliz's result but it is measured to be 650 ºC in Demirbas's result. Both of them used similar batch process reactor and thermo gravimetric analysis. According to the provided schemes, the most likely reason is the difference in the temperature measurement location where the temperature sensors were located. There was significant temperature gradient along the apparatus in which the melted plastic at the bottom of a fix-bed batch reactor had much lower temperature than that on the top surface of the reactor. It was also found that the space temperature in the pyrolyzer was strongly influenced by the product vapour. Different locations of the temperature sensors in different studies are believed to be one of the most important factors on the different cracking temperature reported. Karaduman investigated the temperature profile along a tube heated by external furnace. Large temperature variation was observed between the ends and the centre of the tube.[19]

2.1.4. Type of reactor

The reactor type for the plastic pyrolysis significantly influences on the heat transfer rate, mixing of plastics with pyrolysis products, residence time and the reflux level of the primary products. Reactors can be classified into batch, semi-batch and continuous or classified based on types of reactor bed. [20]

Batch, semi-batch and continuous reactors

According to the feeding and product removal processes, the pyrolysis reactor is categorized into batch, semi-batch and continuous reactors. In the batch reactor, the materials are fed into the reactor in batches for pyrolysis either at the start of the process or after all of the fed materials are processed. In the continuous reactor, the feed materials are input from one part and the products are led out from the other part of the reactor [21].A semi-batch reactor removes the pyrolysis products continuously once they are generated but the feed materials are added initially before the pyrolysis process starts. Some semi-batch process uses inert carrier gas to help remove the pyrolysis products. Particular reactions and phenomenon such as secondary pyrolysis may occur in semi-batch reactors and does not occur in batch reactors. Fixed bed, fluidized bed and screw kiln reactors Based on the heat transfer methods and flow patterns of the feedstock and products, the pyrolysis reactors can be classified into fixed bed reactor, fluidized bed reactor and screw kiln reactor. In the fixed bed reactor, the pyrolysis occurs on a stationary bed which is easy to design and operate [22]. However, the irregular sizes and shape of the feedstock plastics may cause feeding problems in continuous process and the low thermal conductivity of the plastics results in large temperature gradient in batch process devices. In some systems, the fixed bed reactors are only used as the secondary pyrolysis reactor because the products from the primary pyrolysis are mainly in liquid and gaseous phase which can be easily fed into the fixed bed.

In recent years, a new reaction system named screw kiln reactor has been widely applied for plastic processing. In this type of reactor, here is an extruder to screw the feedstock from a feeder in an oxygen free environment. The extruder is heated by external heat sources. Solid residues and pyrolysis products are separated and collected from the other end of the extruder. The high viscosity of plastics is not a problem for the flow in screw kiln reactor because the flow is driven by the external motor. Melted plastic or even plastic solid particles can be fed into this reactor. The small diameter of the extruder and good mixing of the materials make the radial temperature gradient negligible. The process is relatively stable and does not use bed material as in the fluidised bed reactor. The feeding rate can be controlled by adjusting the rotation speed of the extruder, which also determines the residence time of plastics.

2.1.5. Residence time

The definition of residence time differs in various studies. In fast pyrolysis or continuous pyrolysis process, it refers to the contact time of the plastic on the hot surface throughout the reactor. However in slow pyrolysis and batch process, the residence time means the duration from the time when feedstock plastic start to be heated to the time when the products are removed. Longer residence time favours a further conversion of the primary products thus yielding more thermal stable products such as light molecular weight hydrocarbons, non-condensable petroleum gases. In a slow pyrolysis, long residence time encourages the carbonization process and produces more tar and char in the products [27].

2.1.6. Other Influencing factors

There are a number of other factors which also affect pyrolysis process to a certain extent. For example, reactive additives such as air, oxygen, or hydrogen are sometimes present in the reaction for different purposes, **which will interfere with the reactions and affect the quality of the products** [28].

Further pyrolysis of the primary product occurs in most processes. Secondary cracking reactions were found in many reports which are enhanced by high pressure, long residence time, low heating rate and high refluxes. Although many researchers observed the impact of secondary cracking, few have investigated the influence of secondary cracking process on the yield and the quality of the products. Most secondary cracking occurred during the pyrolysis of PE and very limited cracking was found in PS pyrolysis. This is possibly due to the difference in their primary products. The primary products produced from PE pyrolysis contain large proportion of heavy hydrocarbons with carbon chain number up to 80. The average molecular weight of the primary products from PE is much higher than that of other plastics, PS, PP, PVC and PET. The secondary cracking is mainly effective for heavy hydrocarbons, hence, has less effect on the pyrolysis of PS, PVC, PET and other plastics. The importance of secondary cracking on PE pyrolysis has intensively been studied in this research [29].

2.1.7. Multi-factor effect on pyrolysis process

Yang et al. studied multi factor effect on pyrolysis process. It is difficult to directly compare the product yields obtained for a specific plastic in different researches as the operating conditions and reactors can be very different. In general pyrolysis processes, thermal degradation occurs in the initial stages of the pyrolysis with absence of oxygen. The pyrolytic products immediately after the pyrolysis consist of solid residue, oil vapour and non-condensable gases among which the oil vapour will become liquid after cooling down. According to the residence time or the heating rate during the pyrolysis process, the pyrolysis can be classified into slow carbonization, slow pyrolysis, fast pyrolysis, and flash pyrolysis. With slow heating rate (less than 10K/min), the carbonization occurs and the process proceeds from the outer surface to the core of the plastic particles with the local carbonization temperature of above 300 ºC. The carbonization process is determined by the heat transfer rate to the material surface and the heat transfer rate within the material. At given temperature and heating rate, the residence time is also the most important variable to achieve the desired carbonization. The residence time required is also related to the dimensions of the material. If the size of material is too large which needs much longer residence time, incomplete carbonization may occur at the centre of the plastic particles[30].

On the other extreme situation, if the operation temperature is very high, for example 800 to 1000 ºC, gasification process occurs and in this case, the plastics are directly converted to short chain gases and the yield of non-condensable gases in the product is maximized. High heating rate is required to minimize the proportion of solid char production and rapid quenching favours the liquid production before further cracking into gaseous products [32].

The above mentioned processes are applied to all of the plastic types to be examined including HDPE, LDPE, PP, and PS all of which have similar cracking temperature from 320 to 500 ºC. However, in the pyrolysis of PVC the cracking temperature (250 ºC) is much lower than that of other common plastics mentioned above[33].

In most practical pyrolysis processes, particularly those applied in industries, preheating and melting the plastic feedstock between 200 and 300 ºC are applied in order to reduce the volume of the feedstock and to eliminate the oxygen from the feeding system. The melting temperature is also high enough for PVC to crack and form hazardous gases and acid. Therefore, a preheating chamber is commonly used in the commercial process to remove gases generated from the PVC degradation in the preheating.

2.2. Existing Commercial Plastic Pyrolysis Technologies and Processes

The waste plastic pyrolysis plants were developed and built in many countries. The selection of the process and the plant is determined mainly on the feedstock composition and the target products. [34]

2.2.1. Feedstock effects

According to a summary of existing processes and technologies reported by Arena and Mastellone, the most important property of plastic feedstock is whether it contains PVC. PVC pyrolysis has different the thermal cracking process and different products from those of other common waste plastics including PE, PP and PS. In the PVC pyrolysis, the products containing HCl are particularly hazardous for fuels. If the feedstock contains PVC, the plants must have re-treatment system to remove and a solvent scrubber to remove HCl from the pyrolysis products. The other important property for some current processes is the size of feedstock. The requirement for the feedstock size is to avoid the feeding blockage and to enhance the heat transfer between the heating medium and the plastics particles. It was found that in most cases, the feedstock is a mixture of various waste plastic in municipal slid wastes or industrial residues. In pyrolysis of the mixed plastics, interactive effects among the different plastic types may occur due to the difference in cracking temperatures and different products. . However, no report has been found where the pyrolysis technology is designed for a specific type of the waste plastic[35].

2.2.2. Technology

The selection of pyrolysis technology is based on the characteristics of the feedstock and the target products. In general, each pyrolysis technology consists of three parts: feeding system, pyrolysis reactor and separation system.

Feeding system

In most commercial processes, the raw materials are firstly heated and melted in the feeding system before flowing into the reactor. The air, moisture and other solid materials can be separated from the raw plastic materials in the feeding system. In addition, the pre-treatment may be required for cracking the PVC at 250 ºC. In some rotary kiln reactors, solid plastic particles with appropriate sizes can be extruded into the reactor directly. Most feeding systems move the highly viscous melted plastics into reactors by its gravity or by an extruder. However, a required temperature gradient should be maintained from the feeding system to the pyrolyzer although this may not be an issue for the rotary kiln reactors. The required temperature gradient is to prevent melted plastic cracking before entering the pyrolyzer. For example, the cracking temperature of PS is 420 ºC thus any over heating in the feeding system should be avoided. Free-fall feeding system is widely applied in fixed bed and fluidized bed reactors[37].

Pyrolysis Reactors

The description and classification of pyrolysis reactors are given in Section 2.1 of this report. Continuous pyrolysis process is applied on most commercial plants with capability to use catalysts in which the plastic retention time is relatively short. Very few of the commercial plants use high pressure operation condition and most of the plants operate at or slightly above atmospheric pressure. The operating temperature in the reactors varies largely from 250 ºC (Mazda fixed-bed catalytic process in Japan) up to 800 ºC (Compact Power fixed-bed pyrolysis in United Kingdom) but most of the pyrolysis reactors operate between 400 ºC and 550 ºC. It must be noted that if the operation temperature is above 800 ºC, the process becomes gasification and the products are mainly short chain hydrocarbons which remains as gases under room temperature and atmospheric pressure. All of the commercial plants are fast or flash pyrolysis. Three types of reactors including fixed-bed, fluidized-bed, and rotary kiln can be found in the literature review[38].

Product separation and collection ,the products from the plastic pyrolysis are mainly combustible gases and liquids. The liquids can be either combusted for power generation or for further refining to produce high quality fuels. In some plants, the pyrolysis products are simply separated into liquid, gas and solid whereas others have a more complete separation system by feeding the mixture of liquid and gas into distillation columns. Diesel range products can then be distilled out as in an oil refinery process. The non-condensable gases are mainly made of hydrocarbons, and a minor amount of hydrogen and carbon monoxide. The gases can be liquefied as fuels, or used as fuels to heat the pyrolysis reactor, or if the amount is insignificant, the non-condensable gases are sent to an incinerator flaring off with the air. Ash may present in the non-condensable gases so most commercial processes have a gas scrubber for cleaning the gases.

2.3 REVIEW PERTAINING TO TESTING OF PLASTIC PYROLYSIS OIL IN AN ENGINE

Kalargaris et al. carried out an experiment to analyse and understand the combustion, performance and emission characteristics of a diesel engine running on an oil which was derived from the pyrolysis of waste plastics. The tests were performed on a diesel engine gen-set. The blending ratio with diesel was varied from 25% to 100%. The following conclusions can be drawn from the test results: [39]

The testing results suggest that for the long-term running, a blend of 60% – 70% PPO operating at 80% – 90% engine load seems to have the most promising potential to achieve the best engine performance and emissions. More parameters such as injection timing, injection pressure and cetane number improvers need to be explored in order to obtain the optimum engine performance.

Plastic waste is an ideal source of energy due to its high heating value and abundance. It can be converted into oil through the pyrolysis process and utilised in internal combustion engines to produce power and heat. In the present work, plastic pyrolysis oil is manufactured via a fast pyrolysis process using a feedstock consisting of different types of plastic. The oil was analysed and it was found that its properties are similar to diesel fuel. The plastic pyrolysis oil was tested on a four-cylinder direct injection diesel engine running at various blends of plastic pyrolysis oil and diesel fuel from 0% to 100% at different engine loads from 25% to 100%. The engine combustion characteristics, performance and exhaust emissions were analysed and compared with diesel fuel operation. The results showed that the engine is able to run on plastic pyrolysis oil at high loads presenting similar performance to diesel while at lower loads the longer ignition delay period causes stability issues. The brake thermal efficiency for plastic pyrolysis oil at full load was slightly lower than diesel, but NOX emissions were considerably higher. The results suggested that the plastic pyrolysis oil is a promising alternative fuel for certain engine application at certain operation conditions[39].

Tian at al. suggested and proved that **c**hemical recycling is an attractive way to address the explosive growth of plastic waste and disposal problems. Pyrolysis is a chemical recycling process that can convert plastics into high quality oil, which can then be utilised in internal combustion engines for power and heat generation. The aim his work was to evaluate the potential of using oils that have been derived from the pyrolysis of plastics at different temperatures in diesel engines. The produced oils were analyzed and found to have similar properties to diesel fuel. The plastic pyrolysis oils were then tested in a four-cylinder direct injection diesel engine, and their combustion, performance and emission characteristics analyzed and compared to mineral diesel. The engine was found to perform better on the pyrolysis oils at higher loads [40].

The pyrolysis temperature had a significant effect, as the oil produced at a lower temperature presented higher brake thermal efficiency and shorter ignition delay period at all loads. This oil also produced lower NOX, UHC, CO and CO2 emissions than the oil produced at a higher temperature, although diesel emissions were lower.

Rinaldini et al. showed that an interesting alternative to fossil fuel for Diesel engines is the use of Diesel-like oil from plastic wastes: such a solution yields the double advantage of recovering the valuable energy content of wastes, as well as of mitigating the disposal problem of the very large amount of plastic wastes produced by both domestic and industrial activities. He described the experimental campaign carried out on a current production indirect injection, naturally aspirated diesel engine, running on standard Commercial Diesel Oil (CDO) and on a Waste Plastic Oil (WPO) derived from the pyrolysis of plastics. Tests have been carried out at both full and partial load, while in-cylinder pressure traces have been measured in order to analyze the combustion phase. The results of the experimental campaign showed a slight reduction of engine performance for the WPO, basically due to a lower volumetric fuel rating, but better brake specific fuel consumption and brake fuel conversion efficiency (differences up to 8%). In-cylinder pressure traces, measured at the same load, revealed some difference in the first part of the combustion process, in particular at high speeds, where for WPO heat release is smoother. Engine soot emissions are always lower running on WPO, with difference up to 50% at full load[41].

Chapter 3

SYSTEM DEVELOPMENT AND EXPERIMENTAL PROCEDURE

3.1 Polymer Materials Collected

For the process of conversion of plastic into usable fuel we selected LDPE plastic products ex. used plastic polythenes. The feed material was collected from various sources in the college itself. Plastic bags were collected. Recycled LDPE plastic can also be used directly in the reactor. The picture below shows the material, which we collected.

Fig 3.1: The waste plastic materials collected.

3.2 Conversion of LDPE polybags into LDPE pellets .

The polybags that were collected were cut down using scissors into small pieces so that they can be inserted into the reactor easily. Also after shredding the effective surface area of the material that will be heated is increased during the melting process. Cutting down the plastic into pieces also increase the chances of proper decomposition of the plastic. Heat transfer area is also increased, this automatically reduces the residence time of the feed material. And thus efficiency of the process is also increased. After shredding of the feed material it was taken directly for the melting process

3.3 Heating the feed material

For heating and pyrolysis purpose a spherical reactor was designed. It measures 26.2 cm in diameter and 30 cm in height. It was made up of toughened glass. The reactor vessel was quite light, weighing just 230 gm. The conductivity of the glass is alo good as the thickness of the vessel shell was very low. If cast iron reactor vessel was used then it would have taken more time to heat it and up to reaching final temperature of 600^{o}C. Thus this was an good option of selecting glass reactor up to a limiting temperature range, cost wise and also efficiency wise. But special care was taken while handling the reactor also while heating it, proper heating rate should be provided to it.

3.4 Thermal decomposition

Pyrolysis or thermal decomposition breaks down the long polymer chains into lower molecular chain. This is done by applying heat in oxygen free environment at atmospheric pressure. If some oxygen is present in the reactor then the plastic would get oxidized and yield will be decreased so it should be made sure that oxygen is not leaking into the reactor. The reactor was sealed properly to make it oxygen free heating. The reactor vessel was having 3 necks, one for feed in and out one for thermocouple and one for output gas collector. Perfect size cork is used to seal the necks of the glass reactor, and it provided a good seal.

When we start heating the plastic it starts melting at about 130^{o}C and at the temperature of 170^{o}C the temperature remained constant. The phase change of the plastic was taking place at that temperature so the temperature was constant. It remained constant till the whole plastic is melted down. After that the temperature starting rising and boiling started, we can see vapors of plastic inside the reactor very easily.

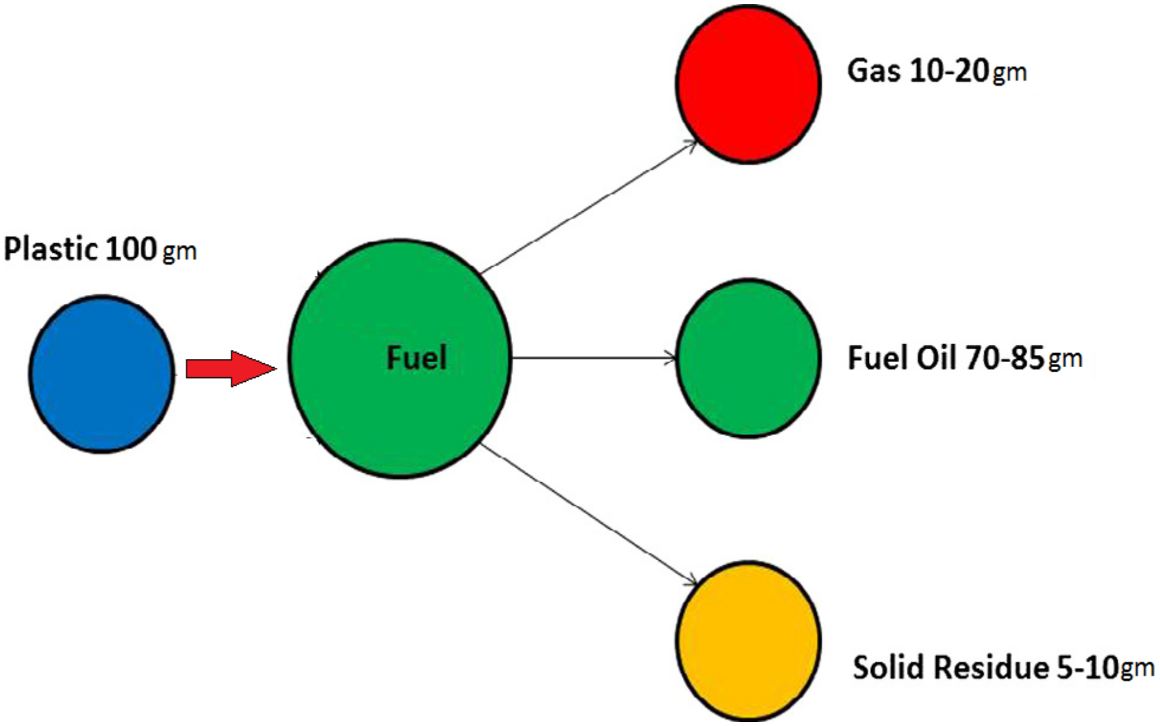

Fig.3.2. Mass balance in pyrolysis process of plastic at a temperature

3.5 Production of liquid oil

The reactor was 70 % packed with the material. The reactor was perfectly sealed with glass cork to prevent the leakage of vapors from the reactor. The reactor was put on an electric heater with the support of a stand. The reactor was placed on the heater such that it does not touch the side of the furnace and is uniformly heated from all the sides. A controller was used to control the temperature. Like if we want to crack the plastic at different temperature then one can set the controller at that temperature. The increasing temperature rate provided was 25°C/min. From one of the outlet of the reactor, vapors of plastic were passed via pipeline connected to the condenser. Now the condensation of the plastic vapors takes place in the condenser. Chiller was used to cool the condenser water. Chiller temperature was set to 10^{o}C. Vapors were condensed and collected in a beaker. Gases which remained uncondensed were very less and probably negligible in quantity because most of them were removed during melting process.

3.6 Setup and Working

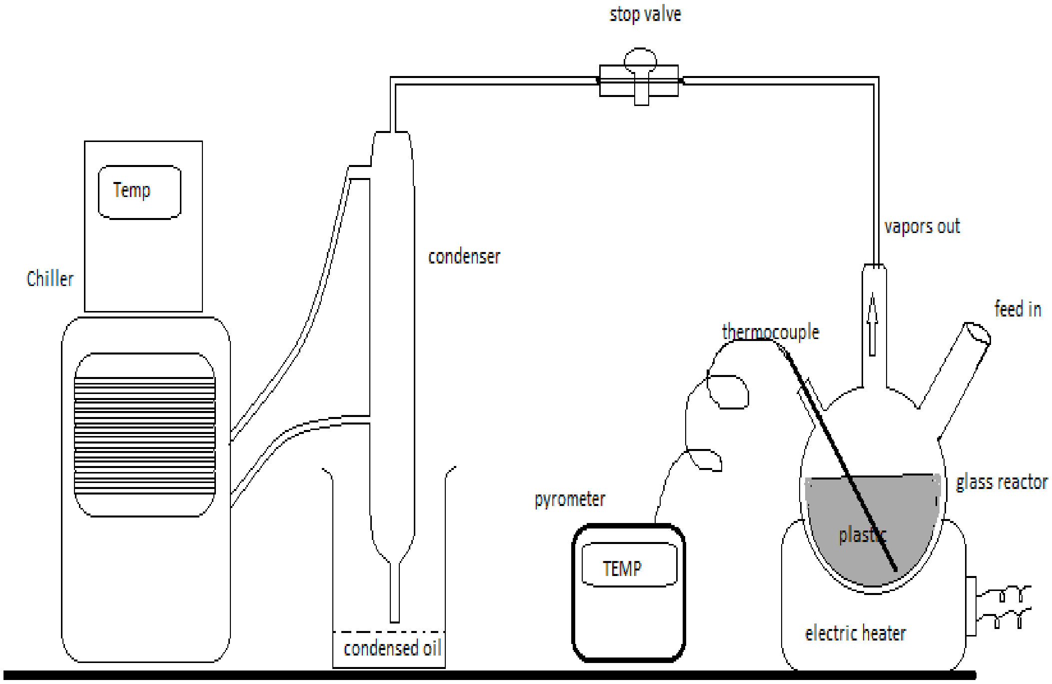

Fig 3.3 Setup for pyrolysis and condensation

The above figure 3.2 shows the setup for pyrolysis of plastic. LDPE plastic pellets are put in the glass reactor, 70 % of the flask is filled with the pellets. An electric furnace of 2 kW rating is used to heat the plastic pellets, it provided sufficient heating rate to melt and boil the plastic. The glass reactor consists of three neck, one for feed in, one for escape out for gases, and one for thermocouple to measure temperature. When we start heating the plastic it starts melting at about 130^{o}C and at the temperature of 170^{o}C the temperature remained constant. The phase change of the plastic was taking place at that temperature so the temperature was constant. It remained constant till the whole plastic is melted down. After that the temperature starting rising and boiling started, we can see vapors of plastic inside the reactor very easily.

The temperature of the plastic in the reactor is displayed in the pyrometer display kept aside. The vapors comes from the reactor and pass through the stop valve, the passage to flow for the gases in the stop valve is very less , thus some of the gases condense at the exit of the valve and rest are condensed in the condenser. The condensed liquid is collected in the beaker. A separate chiller is used to cool the water in the condenser to the temperature of 10°C.

3.7 Analysis of Liquid Products

According to the literature that we went through, the liquid fuel products obtained contains mostly, paraffins, olefins, naphthenes and aromatics (PONA). But due to economic reasons we were not able to find their composition. So, we selected to measure the physical properties like specific gravity, pour point, flash point etc.

Fig 3.4 Oil obtained after pyrolysis

F

Fig 3.5 Color comparison of old and freshly obtained pyrolysis oil

Fig 3.6 Solid carbon residue obtained after cracking

3.7.1. Density

Density is defined as mass per unit volume. This parameter was measured at room temperature with the help of a U-Tube Oscillating True Density meter of make “Anton Paar”, model number “DMA 4500”. The density of diesel along with all blends were measured and compared with density of diesel. The instrument (U-Tube Oscillating True Density meter) used for density measurement is shown in fig 3.4

Fig 3.7: U-Tube Oscillating True Density meter

3.7.2 Viscosity

Resistance of flow due to internal friction of fluid which is subjected to external forces is known as viscosity. During injection of fuel, atomization of fuel takes place which is affected by viscosity. If the variation in the value of viscosity was too low or too high then the mixing of air and fuel as well as atomization of fuel in the combustion chamber may get affected severely. For different test fuels, viscosity was measured in terms of kinematic viscosity. Kinematic viscosity was of liquid fuels were measured using Kinematics Viscometer of make “Petrostat” as shown in the figure 3.3 at $40^{o}C$ as per the specification given in ASTM D445. A standard capillary tube was selected in which a particular amount of fuel is taken that was allowed to flow through the capillary. The schematic figure of the kinematic viscometer is represented in fig 3.5:

To calculate the kinematic viscosity efflux time was measured using stopwatch. The mathematical formula is mentioned below to calculate the viscosity:

$V = c*t$

Where,

V = Kinematic Viscosity

c = constant, (mm^2/sec^2)

t = time in sec

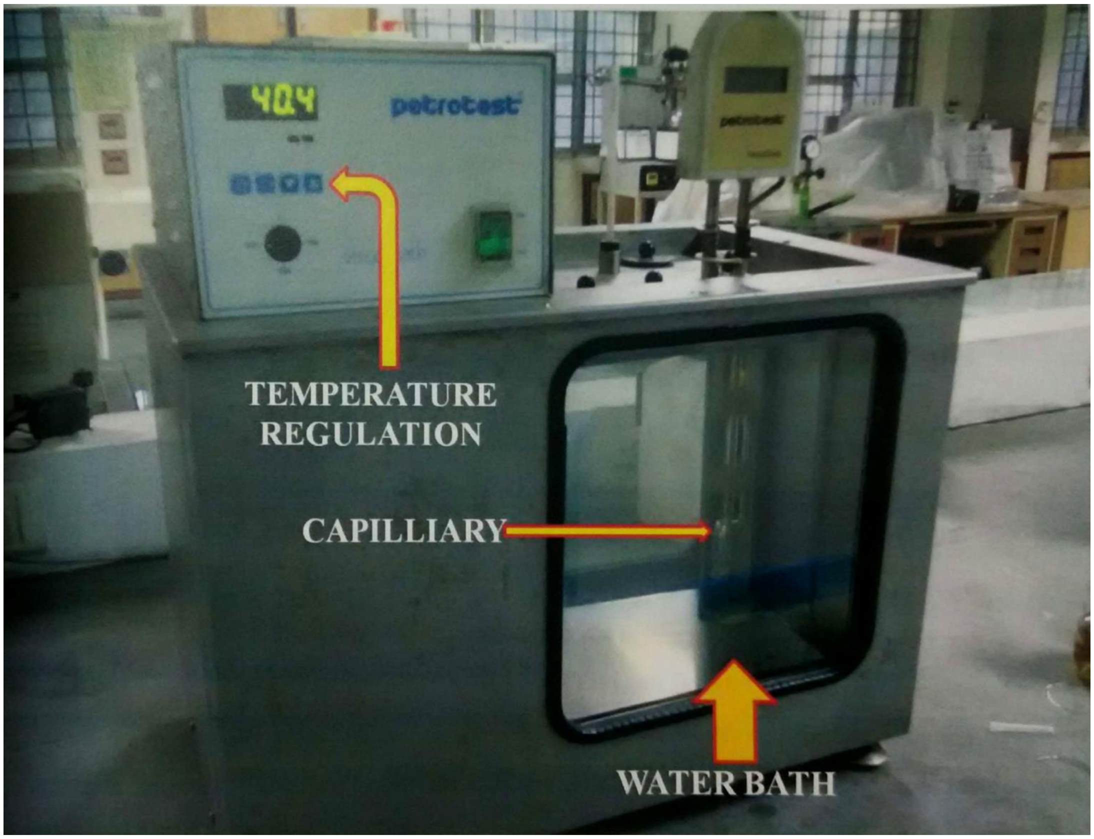

Fig 3.8: Kinematic Viscometer

3.7.3 Calorific Value

The energy contained in a fuel or the food, determined by measuring the heat produced from complete combustion of a specified quantity in it which is generally expressed in joules per kilogram. This parameter was determined with the help of an Isothermal Bomb Calorimeter. The calorimeter model was “Parr 6100 Calorimeter”. At constant volume, the combustion of the fuel takes place in the presence of oxygen. The ignition of fuel was done by electrical method. Oxygen was supplied by cylinder which had compressed oxygen. After few minutes, the fuel had burnt completely and the results were displayed in the instrument. The schematic diagram of corresponding bomb calorimeter is represented in Fig 3.6:

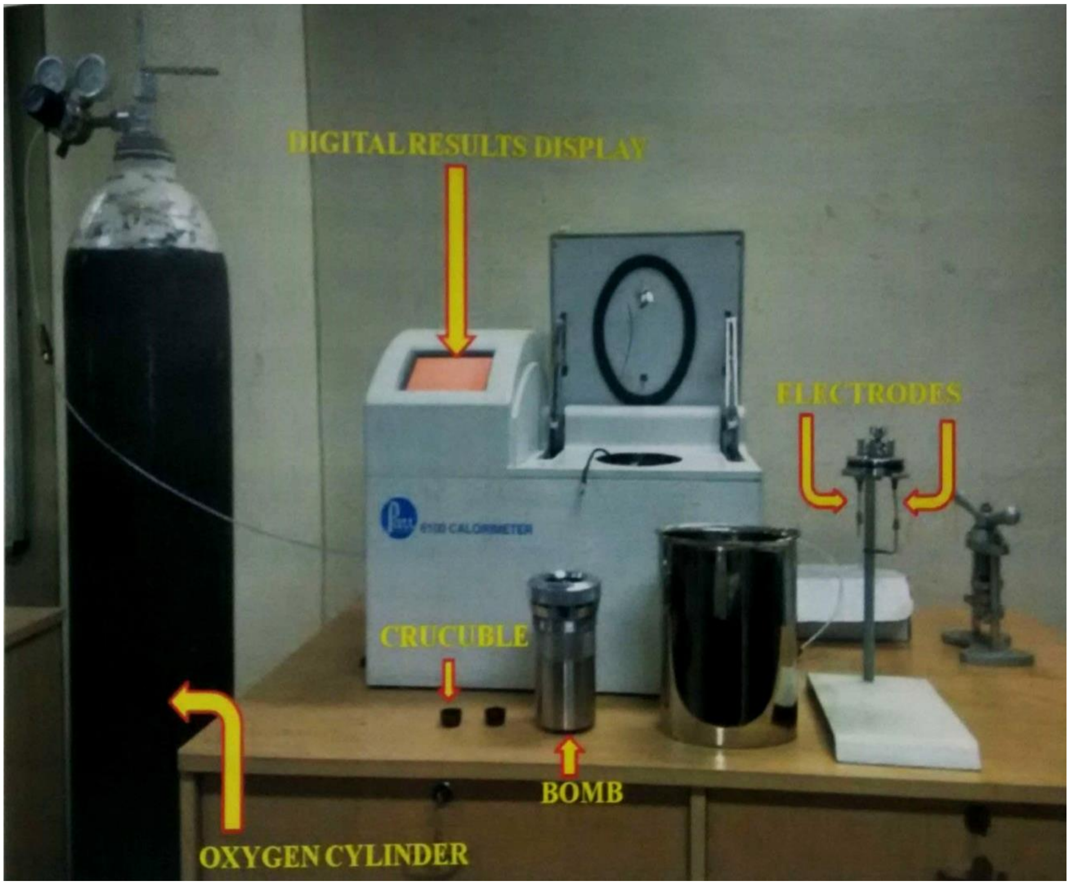

Fig 3.9: Parr 6100 Bomb Calorimeter

3.7.4 Specific Gravity

A 10 ml specific gravity bottle was used to find the specific gravity of the sample. A pipette was taken and 10 ml of the sample fuel was filled in a pre- weighted bottle. The bottle was weighted again. This will give the sample weight , when divided by 10 it will give the specific gravity and from which density is calculated.

3.7.5 Pour Point

To determine the pour point , sample was placed in the test tube and then place whole thing in an Ultra Low Temperature Refrigerator. This refrigerator can provide temperature condition upto -85^oC. The sample was taken out at every 5°C temperature drop to determine its fluidity. A point will come at which liquid stops to flow, the temperature at that point will be the pour point of that fluid.

3.7.6 Flash Point

Flash point is calculated by utilizing Pensky Martin Apparatus. Apparatus contains a cup in which 30 ml of sample is filled into it and cooled by water bath. Continuous stirring is also carried along with it. Sample's vapor are exposed to flame for every 1^0C temperature fall. A point will come at which sample will catch fire with flash, this will be flash point.

3.8 ENGINE TESTING

3.8.1 Engine selection

Indian economy is the one of the pillars of development of India. Due to the high efficiency and rough use of diesel engine, they can be easily used in transportation, agriculture and industrial sectors which ultimately lead to strong Indian economy. On the other hand they also emit unwanted and harmful emissions leading to polluted environment. Hence it is essential to regulate the trend of increasing emissions by modifying the fuel in CI engine which is the major parameter to have a considerable change in the atmosphere. Concerning about practical aspects, a commercial diesel engine, which is generally operated in the above mentioned sectors, has been chosen for the current experimental procedure.

3.8.2 Experimental Test Rig

Setup contains single cylinder, four stroke, air cooled (radial cooled), vertical, totally enclosed, direct injection, cold starting, naturally aspirated , gravity feed fuel system with efficient paper element filter , force feed lubrication to main and large end bearing and camshaft bush diesel engine that is connected to dynamometer (eddy current type loading). The test rig is represented in plate 3.7. There is a provision with necessary instruments for measurement of combustion pressure and crank angle. It is also made for airflow, flow of fuel, temperature analysis and measurement of load. There is a panel box contains air box, two fuel tanks for fuel test, manometer, fuel measuring unit. There is a rotameter installed for measurement of flow rate of fuel. The final setup enables the measurements of various important parameters like brake thermal efficiency, indicated mean effective pressure, brake mean effective pressure, frictional power, mechanical efficiency, specific fuel consumption, indicated thermal efficiency, A/F ratio, brake power and indicated power.

The technical specification of the corresponding engine are listed below in table 3.2

Table 3.1: Technical specification of the diesel engine

Make	Kirloskar
No of cylinder	1
Bore x stroke	95 x 110mm
Cubic capacity	0.78 Lit.
Compression ratio	17.5:1
Rated output as per BS514/ISO 3046/ISO 10001	5.9 KW at 1500 rpm
Starting	Hand start with cranking handle
SFC at rated hp/1500 rpm	251 g/KWh
Fuel tank capacity	11.5 lit.
Fuel tank refilling time period	Every 6.9 hours engine running at rated o/p

Engine weight w/o flywheel	118 kg
Weight of flywheel	64 kg
Rotation while looking at flywheel	Clockwise
Cooling system	Air cooled
Dynamometer	Eddy current

3.8.3 Setup

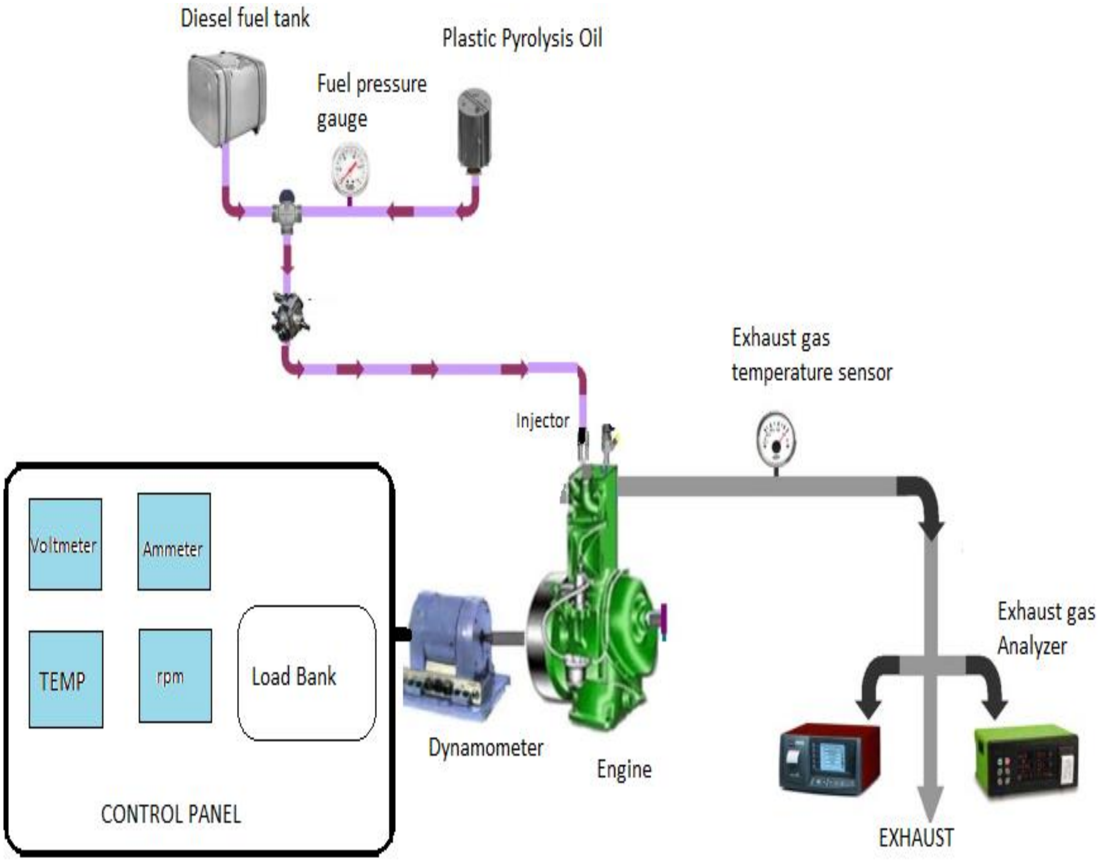

Fig 3.10 Schematic diagram of experimental test rig

For measurement of voltage and current, voltmeter and ammeter were connected between alternator and load bank. A nut was welded on the flywheel with the installation of photo reflective sensor that is mounted on the bracket which is linked to the engine. For measurement of the exhaust temperature, installation of thermocouples is done at exhaust manifolds. For the analysis of exhaust gas temperatures AVL 437 smoke meter and AVL Di gas analyser are used.

Thus a system is designed to study the theoretical as well as practical performance of plastic pyrolysis oil and diesel. Additionally it was easy to maintain and handle the engine because of presence of single cylinder. The experiment on the engine could be done on hot climate too because of air cooling system.

3.8.4 Selection of parameters

Engine calculations were done on the basis of specific parameters which were selected sensibly. The test performed on the engine is on the basis of IS:10000. The fundamental parameters needed from the engine are enlisted below:

1. Engine RPM
2. Fuel consumed
3. Temperature analysis
4. Power output from the engine

The parameters mentioned above were calculated by following signals from the test bench.

1. alternator voltage
2. alternator current
3. RPM sensor
4. Exhaust gas temp at inlet
5. Exhaust gas temp at outlet
6. Fuel inlet and outlet across heat exchanger
7. Fuel consumption rate
8. AVL 437 smoke meter
9. AVL Di gas analyser

Based on the selection of parameters, essential instrument were installed for sensing theses parameters in the set-up.

3.9 Exhaust Emission Analysis

There are lot of emissions produced from diesel engine which are analysed by AVL Di-Gas analyser (AVL 4000 Light Model). It was done mainly for analysis of unburned hydrocarbon, CO, CO_2, and NO_X. To measure the smoke capacity, AVL 437 smoke analyser was used. The fundamental measurement of these instruments was recorder in terms of opacity. Light beam was projected across a flowing stream of exhaust gases, suspended soot particles absorbed the definite portion of light. The remaining part of light strikes on photocell, generating photoelectric current which defines smoke density.

These instruments are calibrated regularly using standard gas mixture. Insertion of sampling probe for smooth flow of exhaust gas was done on the exhaust pipe. Additional mounting of a surge tank at the engine exhaust is done to have consistent exhaust emissions. Technical specifications of AVL Di-gas 4000 light and smoke meter are outlined in following table 3.3

Table 3.2 Specifications of AVL Di-Gas 4000 light and AVL smoke meter

Emissions sensor	Measurement range	Resolution
CO	0-10 % vol	.01% vol.
CO_2	0-10 % vol	.1 % vol
NO_X	0-5.000 ppm % vol	1 ppm
HC	0-20.000 ppm % vol	1 ppm
AVL smoke meter	0-100 % vol	1%

3.8 Calculating the parameters

The performance parameters like brake power, brake thermal efficiency and brake specific fuel consumption are calculated by theoretical approach. The methodology to find out these parameters are described below:

3.8.1 Brake Power

The brake power is calculated by following formula:

$$BP(W) = \; V x\, I$$

Where,

V = voltage recorded by voltmeter

I= Current recorded by ammeter

3.8.2 Brake mean effective pressure

The BMEP is also calculated by following formula:

$$BMEP(bar) = \frac{120\, X\ brake\ power}{L\ x\ A\ x\ N\ x\ 101.325}$$

Where,

L= stroke length(m)

A= piston area (m^2)

N= Engine rpm (rps)

3.8.3 Brake thermal efficiency

This is one of the most important parameter in context to performance of the engine. It is calculated by:

$$BTE(\%) = \frac{brake\ power}{\dot{m}x\ CV}$$

Where,

m= mass flow rate of the fuel (kg/s)

CV= calorific value of the fuel (KJ/kg)

3.8.4 Brake Specific Energy Consumption

The energy consumed to generate one unit of power is known as brake specific energy consumption

$$BSEC\left(\frac{MJ}{kWh}\right)=\frac{m\ x\ CV^{\cdot}\ x\ 3600}{brake\ power}$$

Where,

m= mass flow rate of the fuel (kg/s)

CV= calorific value of the fuel (KJ/kg)

Chapter 4

RESULTS AND DISSCUSSION

The experiment was performed on in CI engine without any modification executed in it. The motive of current study is to operate the diesel engine with the waste plastic oil and the diesel followed by performing the experiment to measure emission and performance parameters. In this chapter, all the physic-chemical properties along with performance parameter and emission parameters have been shown graphically and explained theoretically.

4.1 Pyrolysis monitoring and product analysis

In industries and various researches in the field of plastic pyrolysis different types of plastic and operation conditions are used. So in the literature also we can see significant variation in the quality as well as in the quality of the products. If one is using same kind of plastic along with similar operating condition then the product yield will be of same quality. At the same time we measure the percentage of gaseous products formed as a result of the reactions. The temperature at which plastic is operated is checked using the thermocouples inserted inside the reactor. Pressure gauge is essential for high pressure pyrolysis in order to have a better control over the pressure we need to operate. But in our setup no pressure gauze is used as no accumulation of the gases are there in the reactor. Heating power or heating rate is controlled by the resistance of the electric coil or the current supplied. We can also control other things like feeding rate of plastic and also the rate of flow of gas, by changing the cross section area of the flow of the gas using a flow knob.

4.2. Comparison between diesel and gasoline with plastic pyrolysis oil

Properties such as density, cetane number and range of distillation are all important, when compared to commercial diesels as it indicates the ignition conditions of the fuel. Cetane number signifies how well the fuel is ignited, if cetane number is high then knocking tendency of the fuel is low, and it also controls the operating compression pressure in the cylinder. And also if the fuel is less dense then compression of fuel is easier. There are also some other properties with respect to the flow of fuel such as viscosity, plugging out cold filter, flash point and pour point. Various other properties shows the effect of minorities in diesel like water and sulphur content, carbon residues, ash content and other aromatic hydrocarbon content. There could be chances of tank corrosion and also corrosion of other injecting devices if water content in the fuel is high. Some fuel performance properties consist of color of fuel, particulates, tendency to block filter, lubricating, prevent oxidation and hence reduce corrosion etc. These properties are the outcomes of the above properties. Thus there are various properties on which fuel's quality is based on. The liquid fuel quality obtained from the pyrolysis of plastic will vary according to the operating parameters of the pyrolysis, the type of reactor used and the type of plastic fed. However a comparison is made in the table of various fuel properties of plastic pyrolysis oil, gasoline and diesel.

The plastic derived fuel quality largely depends on the process and type of feedstock. If we investigate the composition of the liquid fuel obtained from the LDPE plastic we can find that it contains same linear alkanes as in the diesel itself.

But if we talk about the storage stability of the fuel, we found that it is decreased because alkene content in LDPE derived fuel is very high than that in diesel. And also high content of linear alkane creates low solubility of plastic derived fuel in diesel.

Table 4.1 Comparison of some properties diesel, waste plastic oil and gasoline

S.NO.	**PROPERTIES**	**WPO**	**DIESEL**	**GASOLINE**
1.	COLOUR	PALE YELLOW	ORANGE	PINK OR YELLOW
2.	SPECIFIC GRAVITY AT 30°C	0.8355	0.84 TO 0.88	0.77
3.	GROSS CALORIFIC VALUE(KJ/KG)	45340	46500	45000
4.	KINEMATIC VISCOSITY, cSt @ 40°C	1.6	3.1	0.9

5.	CETANE NUMBER	51	55	-
6.	SULPHUR CONTENT (%)	< 0.002	< 0.035	-
7.	FLASH POINT °C	42	50	-43
8.	FIRE POINT °C	45	56	-49
9.	POUR POINT °C	< -7	6	-
10.	AROMATIC CONTENT %	55	20	-

Comparison of Thermo Physical Property

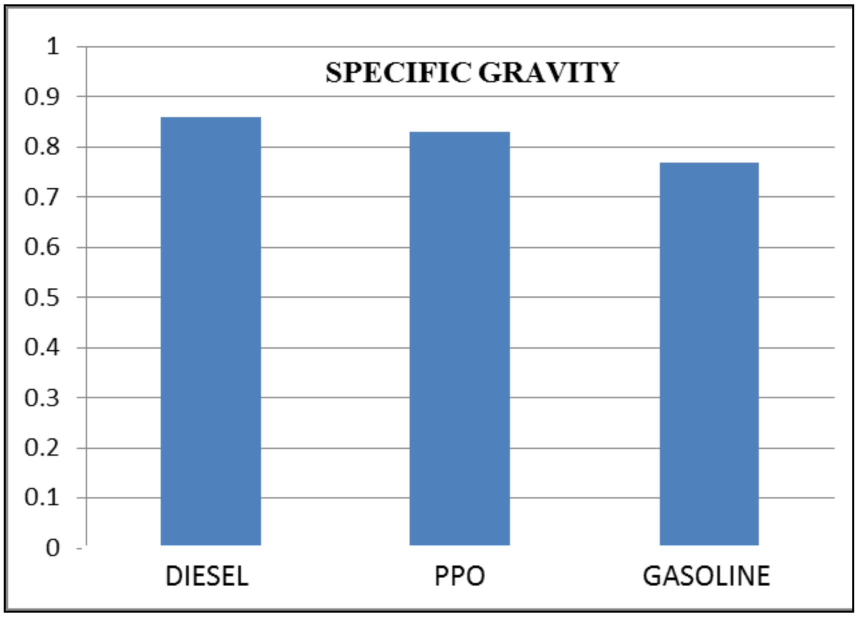

Fig 4.1. Comparison of specific gravity

Specific gravity can be defined as the density ratio of the sample to that of the water (standard fluid). The specific gravity of plastic pyrolysis oil as we can see from the bar graph is in between the diesel and the gasoline. This property tells us that it is suitable for both diesel and gasoline engines but one can't rely on a single property as we go further discussing the other properties we will find that plastic pyrolysis oil is more suitable for diesel engine, for example if we compare the flash point, we can see from the table, then it can't be used in a diesel engine. Flash point of diesel is around 50^oC and for plastic pyrolysis oil it is 42^oC, it is lower than the diesel that it but very high as compared to gasoline, so it can't be used in gasoline engine.

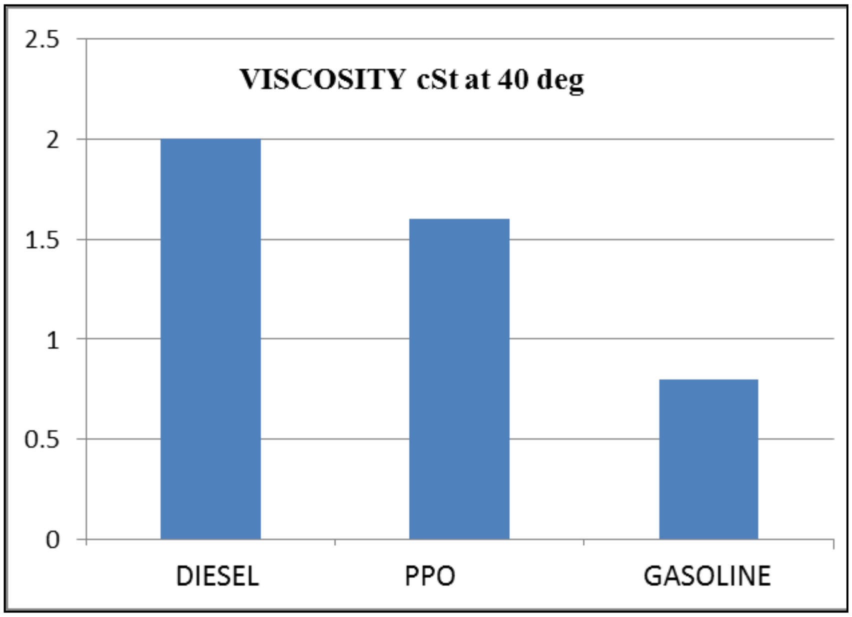

Fig 4.2. Comparison of viscosity

Viscosity is one of the important fluid property whose effect can be observed when the fluid particles are in motion. When the fluid is flowing, different fluid velocities are observed for different fluid elements, so each fluid element feels some sort of resistance because of the friction between the them. This stress is called shear stress between the layers of the fluid element. Sir Isaac Newton have given the relationship between the shear stress developed and the velocity gradient. Ability of the fuel to flow is increased if the viscosity is low. Also viscosity of liquid fuel is increased with the rise in the temperature.

The effect of this property, viscosity, is understood when the fluid is moving. When the fluid is moving, different fluid elements moves with different velocities, then each element of the fluid layer will be in some sort of resistance to flow that is due to friction between the fluid layers. A stress is seen between the layers of the fluid that is termed as shear flow stress

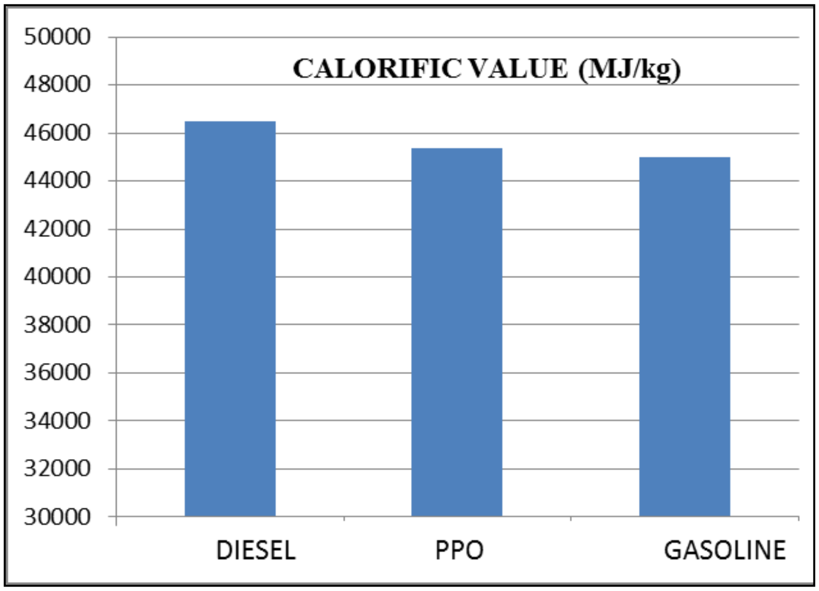

Fig 4.3 Comparison of Calorific value

This is an important parameter regarding engine performance. Calorific value directly affects the BSFC of the test fuels. Calorific value of the fuel to be tested is measured using a bomb calorimeter. Bomb calorimeter is described in previous section. Figure 4.3 shows the values of calorific value for different fuels. Calorific value of the blends was less than that of diesel fuel that will definitely affect the engine performance.

According to the graph as shown in fig 4.3, plastic pyrolysis oil has calorific value in between the range of diesel and gasoline. It is around 45.3 MJ/kg. Still comparatively the energy value of the fuel that is obtained from waste feed is quite good. It is totally behaving like an efficient fuel in terms of viscosity, flash point and calorific value. Now what matters is the performance and emissions obtained from the engine running on the waste plastic fuel. As fuel is less viscous as compare to the diesel, automatically the pumping work is reduced and atomization of the fuel will be easier, better control can be made over the air fuel ratio.

4.3 RESULTS OF ENGINE PERFORMANCE TESTING

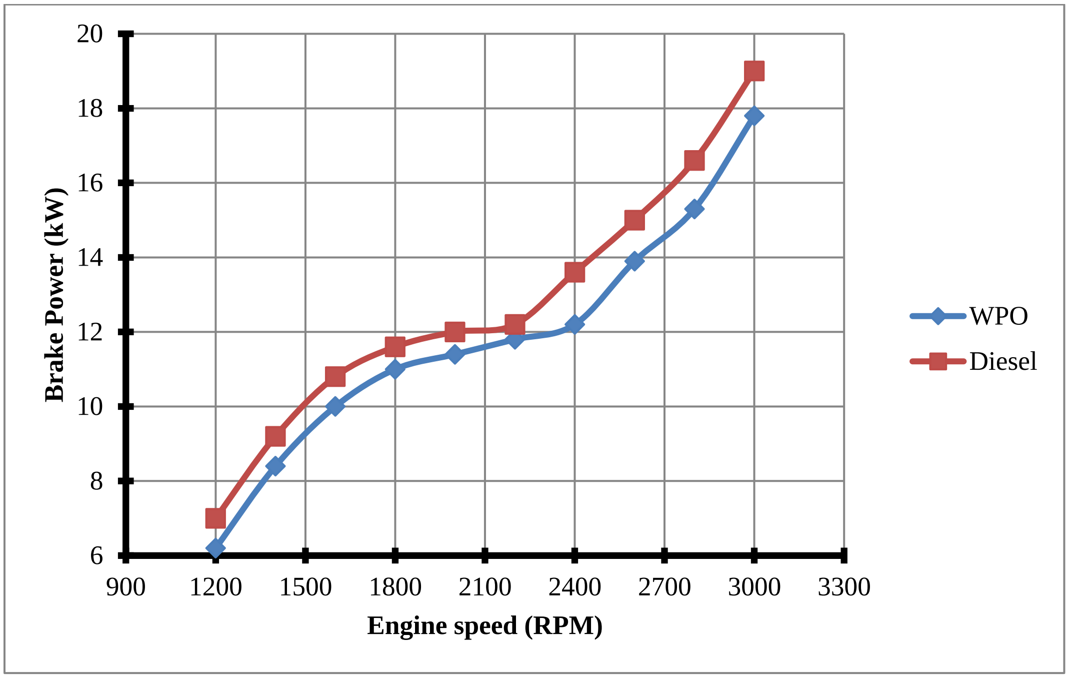

Fig 4.4 Brake power variation with engine speed

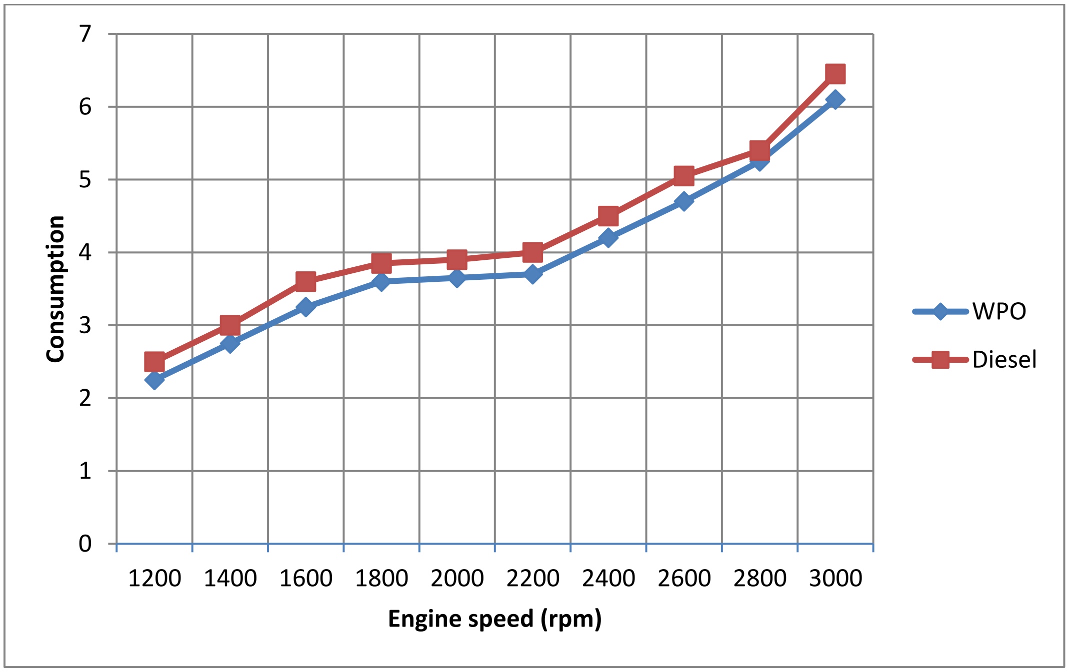

Fig 4.5 Fuel consumption at different engine speed

In above figures, different performance variables are plotted at different engine speed (in rpm).

From Fig 4.5, it can be seen that the volumetric consumption of fuel is reduced with Waste Plastic Oil, the approx. change in fuel consumption rate was observed to be around 8 %. However this result was not expected, as it was thought that the engine will deliver the same volume flow rate at each cycle because a fully mechanical injection system was equipped. This might be due to the difference in the various physical properties of the waste plastic oil and the diesel oil, particularly due to the density and the viscosity. Volumetric efficiency of the pump, which is operated mechanically, is affected by the viscosity and the density of the fuel. As due to these properties a variation is created on flow rate through the clearance gap between the plunger and the liner. More the viscosity lesser will be the flow rate, more the pumping work is required. Similar is the case with density also, denser flows means more force is required to the pump the fuel.

Mostly the larger difference in the fuel consumption was due to the lower density of the waste plastic oil which can be seen in the fuel properties table. Specific gravity of the waste plastic oil is lower as compare to the diesel fuel, as measured. Now the lower flow rate of mass of the fuel also with the low heating value has directly influenced the power and torque, and the difference mostly varied between 6 to 10% between the two fuels.

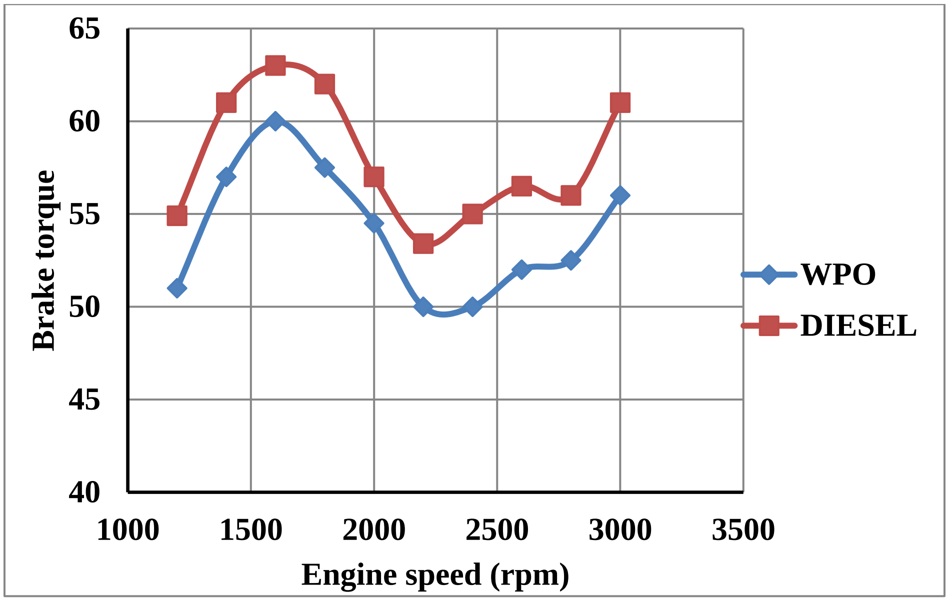

Fig 4.6 Brake torque variation with engine speed

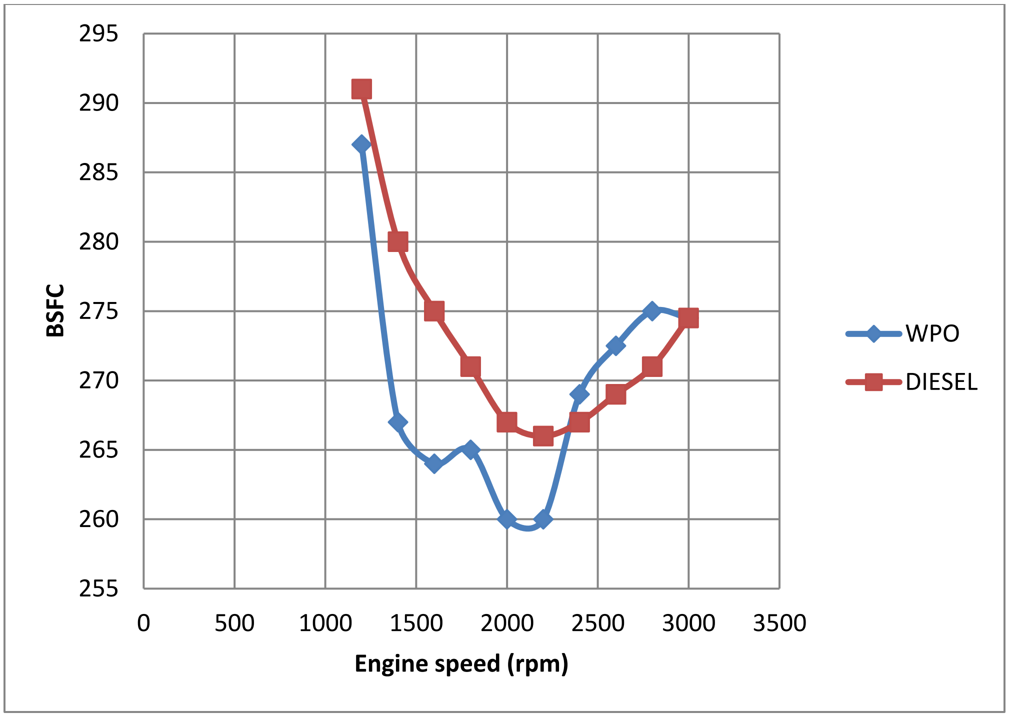

Fig 4.7 Brake specific fuel consumption at different engine speed

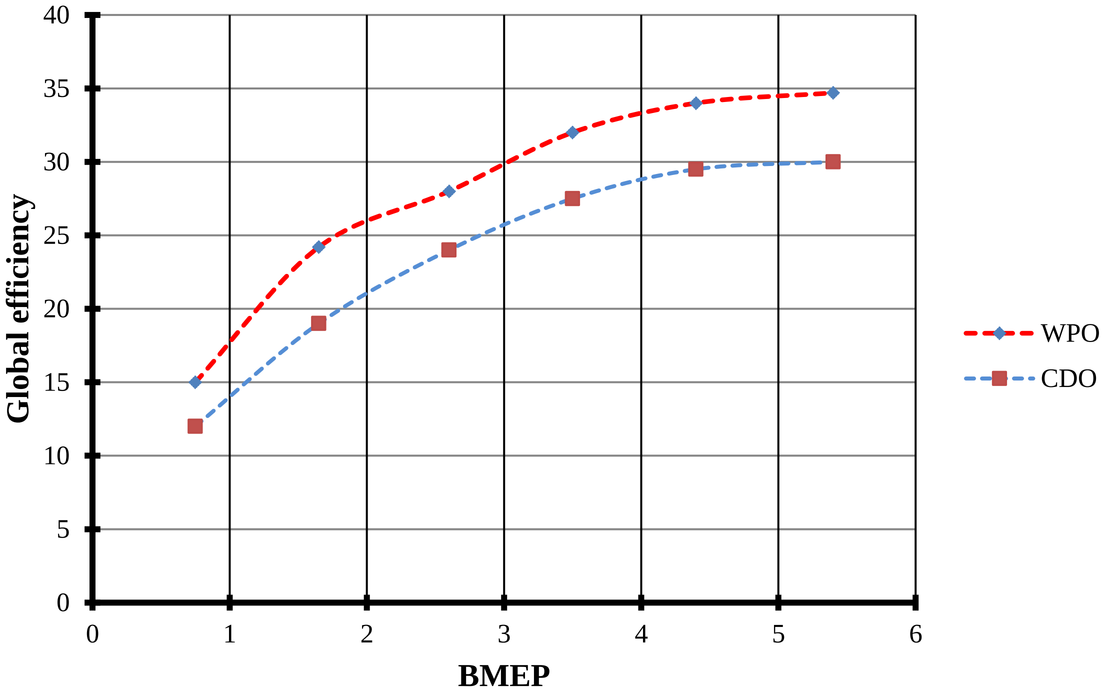

Fig 4.8 Global efficiency with Brake mean effective pressure

In the test performed, engine performance was done considering the brake power, specific fuel consumption, thermal efficiency and emissions also running the engine on both waste plastic oil and diesel oil.

At lower and midrange speeds, there was decrease in fuel consumption with the waste plastic oil except at 3000 rpm (Fig 4.7). But the differences in fuel consumption is not that much, it is just around 2 to 3% and is maximum at 1400 rpm of 4%. The efficiency of fuel conversion is defined as the ratio of brake power to the product of mass flow rate of the fuel and calorific value.

Fig 4.8 shows the global efficiency vs. brake mean effective pressure. It clearly shows the fact that the waste plastic oil has better efficiency, differences is max up to 8%. Better results can be seen at low and mid-range speeds. The reason behind the high efficiency is due to complete combustion of the fuel and also higher air- fuel ratio, means less fuel is injected with same quantity of air.

In other set of tests, diesel and plastic oil were tested and performance is compared in terms of torque and power. Waste plastic oil has less density so brake specific fuel consumption and specific fuel consumption are always less and global efficiency is higher, and that is conforming to the results. If we compare the soot emissions, from literature review it can also be concluded that benefit of waste plastic is also there at partial load conditions, generally at low pressure below 3 bar of brake mean effective pressure. Emissions are also and are very equivalent to diesel emissions, but for higher brake mean effective pressures, emissions are increased and opacity of the exhaust gases are also reduced if we compare with the common diesel oil.

4.4 RESULTS OF EXHAUST EMISSIONS

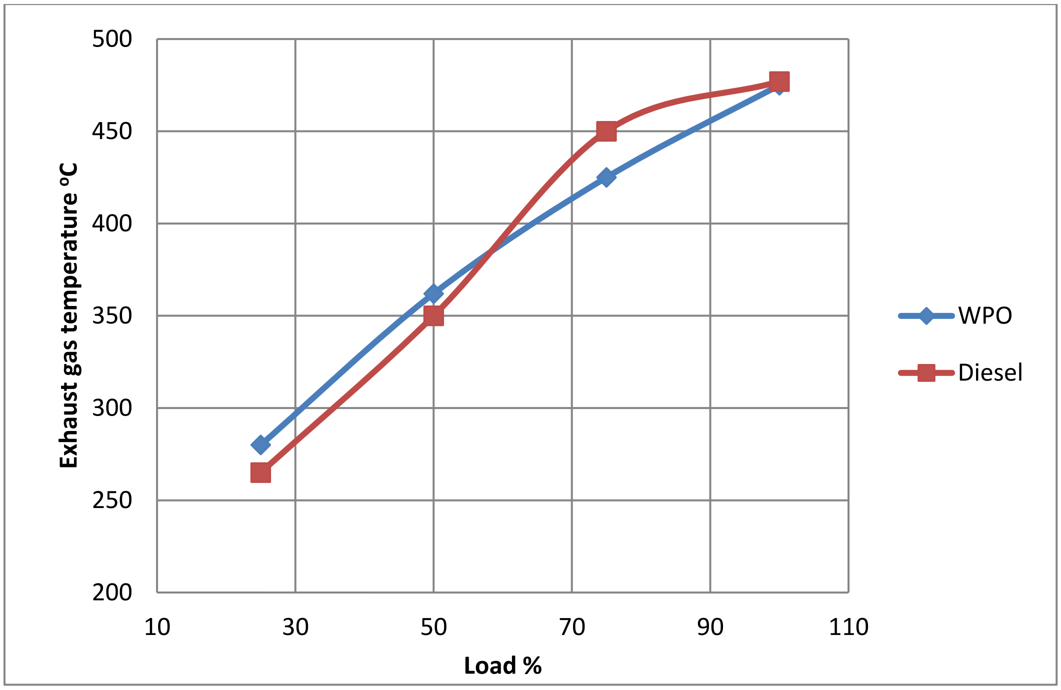

Fig 4.9 Exhaust gas temperature at different load

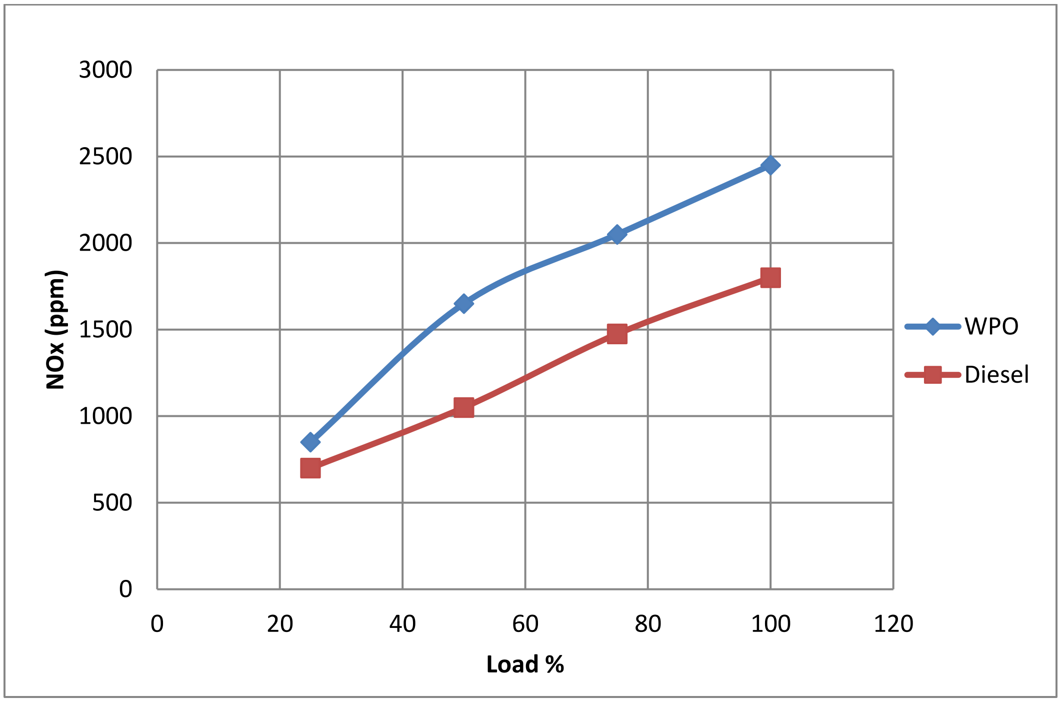

Fig 4.10 NOx Emissions at different load

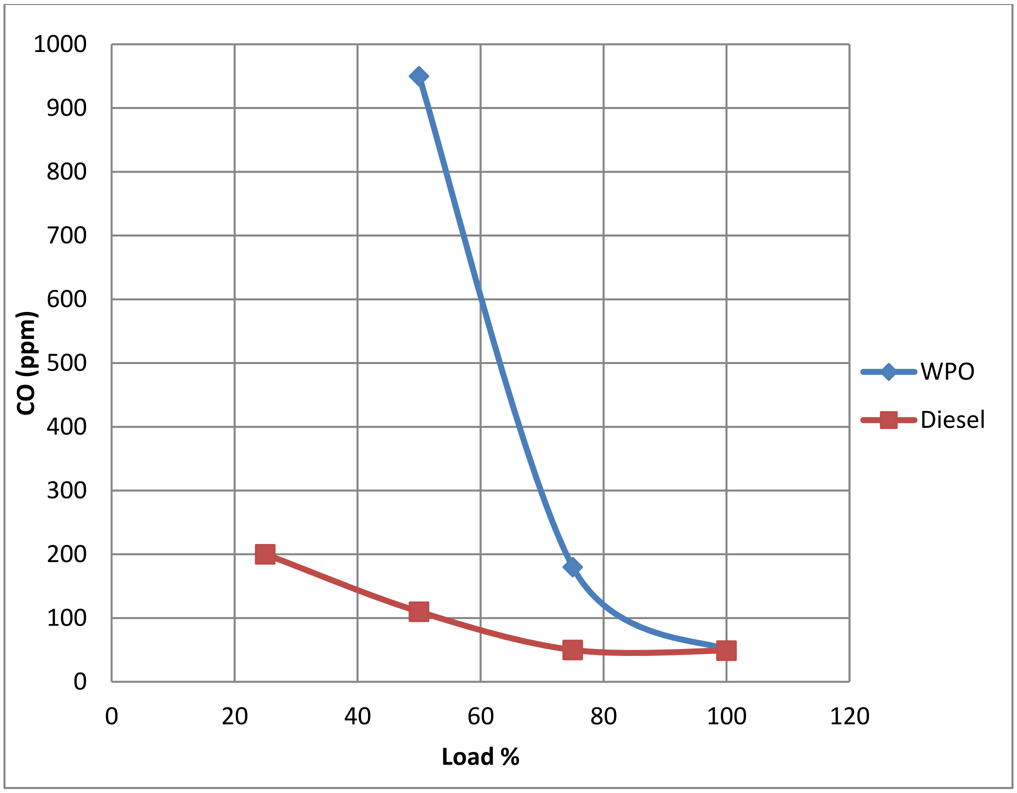

Fig 4.11 CO Emissions at different load

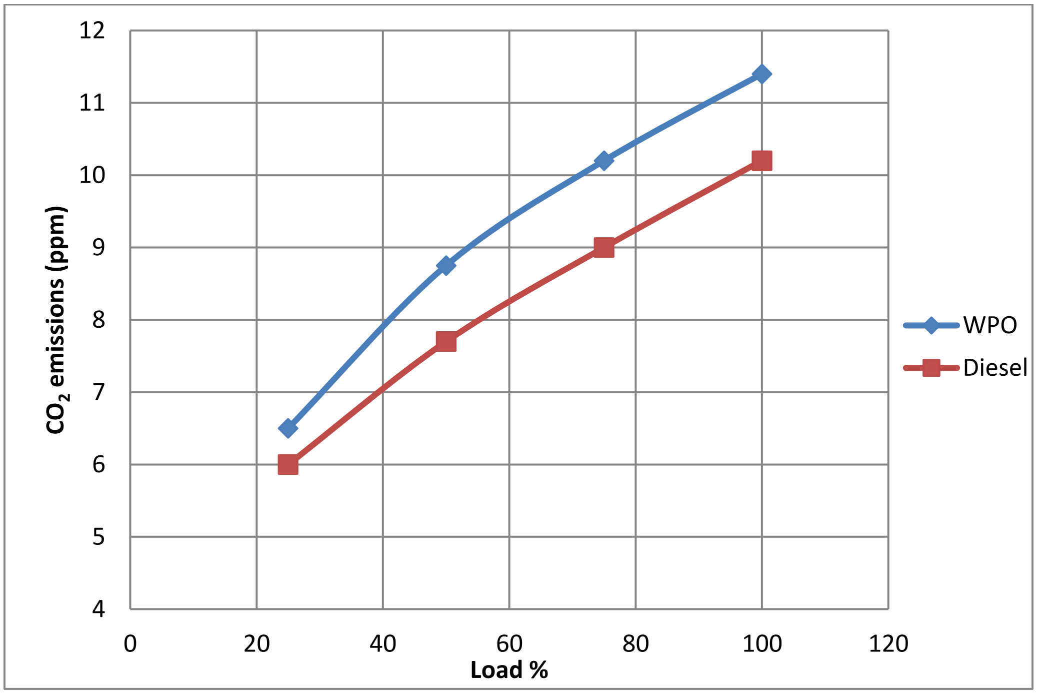

Fig 4.12 CO_2 Emissions at different load

Variation of NOx emissions with the load percentage for both the common diesel and the waste plastic oil is shown in Fig 4.9. There are three NOx mechanism production theories in combustion. They are thermal, prompt and fuel mechanism.

Thermal mechanism is responsible for majority of NOx productions in diesel engine due to high temperature and high oxygen source. According to the results plotted NOx emissions are increasing with increase in the load. This is exactly due to the fact that as the load is increased, temperature is increased, so NOx formation occurs. Ignition delay is also increased thus high portion of premixed combustion, then heat release rates and cylinder temperature is also increased. Automatically NOx emissions will be increased. Another reason for NOx production is the high nitrogen content in the fuel that is production of NOx because of fuel mechanism.

Fig 4.12 represents the variation of unburned hydro carbon emissions. Under mixing and wall flame quenching occurs due to which the unburned hydrocarbon emissions in the exhaust are present. It can be inferred that the unburned hydrocarbon emissions from waste plastic oil is higher as compared to the diesel. Unburned hydrocarbon emissions decreases with the load increasing, similar to the diesel.

The reason for higher unburned hydrocarbon emissions form the waste plastic oil is still not justified. But it can be predicted that it may be due to the high aromatic content in the fuel. Other reason that can be possible is that impingement of spray of plastic pyrolysis oil more effectively to the wall due to its density, lower viscosity resulting in longer ignition delay. Carbon monoxide emission variations with the load for both the fuel are shown in the figure 4.11. Incomplete combustion is the primary cause of these emissions and it is affected by the temperature and the equivalence ratio. From the graph plotted it can be inferred that as the load is increased Carbon monoxide emissions decrease regardless of the fuel.

Carbon dioxide emissions are due to the complete combustion of the fuel. Complete combustion implies that the carbon atoms in the fuel are completely oxidized. Generally it is not checked by the emissions regulators and also it is not considered as a harmful gas. But still carbon dioxide is considered as a greenhouse gas, so it is very important to control or reduce carbon dioxide emissions. Variation of CO_2 emissions with the load are shown in the fig 4.12 for both diesel and plastic pyrolysis oil. It can be seen from the graph that a linear relationship is formed for CO_2 emissions as the load is increased. Now if we consider this result a negative impact is created considering the environment for plastic pyrolysis oil as a fuel. But as we now that this fuel is produced from the waste plastic source which otherwise is burned or landfilled, creating much more bad impact on the environment. That’s why it is still considered that this technology is still very promising and quite sustainable to use waste plastic for combustion.

Chapter 5

CONCLUSION & SCOPE FOR THE FUTURE

5.1 CONCLUSION:

In this study, pyrolysis of the hydrocarbon polymers, LDPE was investigated theoretically and practically. In the investigation some factors have been identified which affects the process of pyrolysis of plastics. Pyrolysis of polymers containing hydrocarbons is a complex process, consisting of huge number of reactions and the products. There are different factors on which the reactions and product yield depends. Different stages are there, plastic undergoes through before decomposition like glassy state, rubbery state and then liquid state, as the temperature is increased. Pyrolysis is thus a process in which decomposition takes place in an inert atmosphere.

The plastic was cracked thermally at temperature range of 500ºC to 600ºC. The products obtained were of different composition and the product yield was different for different temperatures. The liquid product obtained had a specific gravity of 0.7787, kinematic viscosity of 1.6 and calorific value of 45.3 MJ, which is quite good and falls in the range of diesel fuel. These properties do also match with the gasoline range fuels but the flash point is very high. Thus the plastic pyrolysis oil was tested only in the diesel engine.

The engine was able to operate stably on plastic pyrolysis oil at different engine rpm and load. The engine brake thermal efficiency was lower for 100 % plastic pyrolysis oil comparison to diesel. All measured emissions (NOx, UHC, CO and CO2) were higher for plastic pyrolysis oil compared to diesel, however if we use blends of plastic pyrolysis oil and diesel then emissions could be controlled.

5.2 FUTURE SCOPE:

The non-condensable gases were not collected, it would be valuable to collect some of the gases and investigate its composition. The gases if collected have better ignition quality can be compared to the LPG. The diesel range product should be separated out of the condensed products in the semi-scale apparatus. It is worthwhile to add hydrogen into the reaction to saturate the hydrocarbons thus to modify the product to increase the target diesel products.

Hydrogenation can significantly improve the product quality towards transport use.Arrangement of purging nitrogen gas in the reactor to purge out the oxygen completely can be made, it will create better inert atmosphere, thus better fuel quality. Also to decrease the quantity of input energy used by the reactor, one can use specific catalysts.

Chapter 6

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