UNIVERSITY OF SOUTHERN QUEENSLAND

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THE EXPERIMENTAL & SIMULATION INVESTIGATION OF ENGINE PERFORMANCE CHARACETRISTICS OF CONVENTIONAL DIESEL AND WASTE PLASTIC FUEL

Supervisor

Dr. Saddam Hussain Al-lwayzy

A dissertation submitted by

Mr. Abdullah Murad

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ABSTRACT

Excessive consumption of fossil fuels has not only resulted in the rapid depletion of their resources, but also aggravated the environmental pollution. Renewable and eco-friendly resources are required for the sustainability of life on this planet. The plastics, in different shapes and forms, are becoming the most needed materials for daily life activities. They are versatile in their applications because they can be shaped in any form for a desired application. However, their excessive use is causing environmental pollution because they are mostly non-biodegradable and pose toxicity on decomposition. Considering this, researchers are trying to develop processes for recycling plastic waste or convert it in valuable products (e.g. fuel). Waste plastic fuel/oil, can be produced from different sources (synthetic or natural), and is a promising carbon neutral alternative for transport fuels. Different types of waste plastic i.e. low density and high density polyethylenes, polypropylenes and mixed plastics can be thermally converted into oil via pyrolysis process. At present, different methods are being used to investigate the characteristics of produced oil such as effect of reaction time, yield, density and specific gravity. In this study, regular petroleum diesel and waste plastic fuels were tested on a 4-stroke, air-cooled diesel engine Yanmar L48N. The results of regular diesel were obtained from the experimental setup and they were compared with the numerical results obtained using waste plastic fuel. Due to time constraints, the waste plastic fuel studies were only limited to simulation analysis. These numerical results were obtained through modelling simulation of a four-stroke diesel test engine in ANSYS 19.2 software.

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NOMENCLATURE

WPF	Waste plastic fuel
WPO	Waste Plastic Oil
PDF	Petroleum diesel fuel
PET	Polyethylene terephthalate
PVA	Polyvinyl alcohol
PP	Polypropylene
PVC	Polyvinyl chloride
PS	Polystyrene
LDPE	Low density polyethylene
HDPE	High density polyethylene
EVA	Ethylene-vinyl acetate
NOx	Nitrogen oxides
COx	Carbon oxides
SOx	Sulphur oxides
THC	Total hydrocarbons
GHG	Greenhouse gases
EPA	Environmental protection agency

CHAPTER 1. INTRODUCTION

The ecosystem of our planet is rapidly changing due to the burning of fossil fuels, which release different toxic gases and are responsible for global warming. Huge amount of greenhouse gases is being added to the environment through different modes of applications of fossil fuels. The rapid increase in world's population has also increased the energy demands that is adversely affecting the fossil fuel reserves, because of their non-renewable nature (Gupta et al. 2018; Uzoejinwa et al. 2018). Moreover, exceeding fuel prices, environmental concerns, increased awareness for energy efficiency, and global warming, have led to the exploration of new materials for energy resources. These resources should be economical, easy to process, abundantly available, eco-friendly and can address vehicular fuel demands. The renewable energy resources are of great interest for scientific community such as solar, wind, geothermal, hydrothermal, organic, and biomass (Ambat et al. 2018; Hosseinzadeh-Bandbafha et al. 2018; Hazrat et al. 2019).

In recent decades, the increase in population and its modern living style has produced huge amount of polymer and plastic waste, which is dumped or burnt, leading to environmental pollution. Furthermore, its recycling process is also proceeding with low pace (Khan et al. 2016a). These waste materials have high energy contents due to their chemistry and production procedures which is buried without any use (Goudie 2018). The calorific values of PE, PP, PS, and PVC oil have been reported as 43 MJ/kg, 44 MJ/kg, 40 MJ/kg, and 18 MJ/kg respectively (Hazrat et al. 2019). There are different approaches being applied to reduce plastic wastes, such as to make cheap usable products and recycle them in to valuable products.

WPF/WPO has promising potential to limit the GHGs through utilization of different types of waste plastics. Nevertheless, there are some key factors influencing its performance, (1) high NOx (nitrogen oxides) contents released during its combustion, and (2) its high viscosities. Therefore, it is proposed that it can be used in blended form with conventional diesel fuels for reducing GHGs emissions. Moreover, scientific community is trying to overcome these limitations by introducing improvements in engines, using potential fuel additives, and to treat the exhaust gas streams via different technologies. Appropriate fuel additives are potentially preferred over other methods due to the numerous advantages such as no engine modifications and overall economics. The feasibility of additives is based on cost effectiveness, solubility, flashpoint, toxicity and water solubility.

Considering these circumstances, the present study was undertaken to investigate and compare PDF and WPF performance characteristics in a diesel engine Yanmar ln48. The PDF performance characteristics were determined experimentally. Whereas, in case of WPF, they were obtained through modelling simulation of a four stroke diesel engine in ANSYS 19.2 software.

1.1. Aims & Objectives

The prime aim of this research is to investigate the potential of non-recyclable waste plastics as a fuel additive, as well as to encourage waste plastics recycling. The specific objectives of this research are listed as follows,

1. To develop a basic understanding on WPF produced from plastic waste, understand the production mechanisms and its characterization methods

2. To investigate the engine performance characteristics (such as torque, power, composition of exhaust gas emissions etc.) of regular diesel fuel on Yanmar L48N testing stand
3. Based on the experimental findings, investigation of similar performance characteristics for waste plastic fuel through modelling simulation in a four stroke diesel engine
4. To compare the experimental PDF results with the simulation results of WPF and construct a performance map of engine’s output
5. To compare the results obtained in this study with previous research studies

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

It is estimated that about 4 billion tons of different type of waste is produced yearly worldwide. Quantity of produced solid waste is proportional to nation's population and its volume of economy. According to a report published by World Health Organization (WHO), developing countries are suffering from 25% diseases caused by inappropriate waste disposal. A smart approach to manage the waste is to convert it into productive energy such as biogas and biofuels. The recyclability of plastics is also another important aspect that includes the qualitative analysis of plastic polymers. Progressive communities should develop the recyclability procedures and mentoring of people is required to reduce the waste generation to save our land. (Trivedi et al. 2020).

Over the decades, the disposal of plastic waste and its recycling has remained a pertinent issue in developing countries. The awareness in the public is increasing to dispose the waste and utilize it for the betterment of society. Several attempts and procedures are being used in the mechanical recycling of post-commercial, industrial and pre-sorted post-consumer waste, but low-grade mixed plastic waste processing has always shown technical and economic difficulties (Demirbas 2004; Andrady & Neal 2009; Lehmann 2011).

The plastics can be converted into oil products by the breakdown of long polymeric chains to shorter chains. The breakdown of long chains can be attained at moderate or high temperature heating of the material. It can also be done with the help of zeolite catalysts which can enhance depolymerisation rate (e.g. used in oil refineries) (Gao 2010).

2.2. Waste Plastics

Plastics have a pivotal role in daily life and have an edge over traditional materials. They have promising characteristics to be used in different fields due to their low weight, robustness, energy efficacy, ease of production and diversity in design. Every year, the plastic produced all over the world is estimated to more than 100 million tonnes. They have been used in different inventories, as shown in Figure-2.1 (Geyer et al. 2017), but the end of their useful service life results in blockage of drains and health hazard. India is one of the largest plastic waste producers, about 5 million tons in 2012 (Bajad et al. 2017).

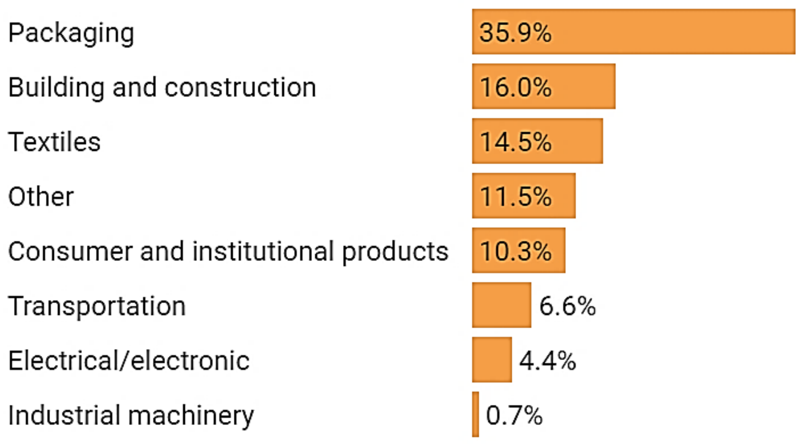

Figure-2.1: The use of plastics in different fields *(Beckman August 9, 2018)*

Plastics are broadly classified in to two categories depending upon their properties and thermal behaviour. They are further discussed in next section.

2.3. Types of Plastics

There are many different classifications of plastics depending upon the structure, source of origin, polymerisation degree, and so on. Plastics can be generally categorized in two broad types based on their physical behaviour to temperature, namely thermoplastics and thermosets (Carraher Jr 2017; Rajaram.T.Karad 2107). These two classifications are further elaborated as follows,

2.3.1. Thermoplastics

Thermoplastic polymers are solid at room temperature, but when heated, they become soft and are easily moulded in different forms/ shapes or recycled easily. This is because in these polymers, repeating units or monomers are cling to one another due to weak forces i.e. van der Waals forces. As a result, monomers in thermoplastics are arranged in such a manner that closely resembles to mixing of many strands of pearls. They are widely applied in the manufacturing of pipes, adhesives, ropes, belts and insulators. These polymers have specific characteristics such as enhanced strength and ability to retard shrinkage. High manufacturing cost and heat melting are the major limitations associated with these types of polymers (Mayer April 30, 2018). The examples of thermoplastics are presented in Table 2-1. Different thermoplastics and thermosets (Ahmad et al. 2017).

2.3.2. Thermosets

Thermosets are normally as liquid or malleable solid, but upon heating, attain a specific shape. This change in the physical state is irreversible and involves chemical reactions that may occur due to a catalyst, heat, UV light or oxygen. Common examples include phenol formaldehyde and urea formaldehyde (Crawford 1998; Dodiuk & Goodman 2013). In daily life, we use numerous materials in which thermosets are basic building blocks such as composites, varnishes, adhesives lacquers, rubbery stuff (vulcanized rubber), which is effectively applied in shoe soles, tires, and hockey pucks. Different types of thermosets are also shown in Table 2-1. Different thermoplastics and thermosets (Ahmad et al. 2017) and types of recyclable plastic wastes are shown in Table 2-2. Types of recyclable plastic wastes (Williams & Williams 1999).

Table 2-1. Different thermoplastics and thermosets (Ahmad et al. 2017)

Thermoplastic polymers	Thermosetting polymers
PET	Bakelite
PVA	Epoxy resins
PP	Melamine resins
PVC	Polyesters
PS	Polyurethane
LDPE	Urea-Aldehydes
HDPE	Alkyd resins

Table 2-2. Types of recyclable plastic wastes (Williams & Williams 1999)

Type 1	PET	Drinks
Type 2	HDPE	Plastic bags, bottles, toys
Type 3	PVC	Oil bottles, vegetable oil, wrappers

Type 4	LDPE	All types of plastic bags,
Type 5	PP	Bottle tops, bags, some carpets

Plastics can be depolymerized through pyrolysis, gasification or thermal cracking. These thermal methods are widely applied in coal, gas and petroleum refining industries. Few decades back, plastic waste was applied as a feedstock for these processes, but due to different factors, its demand was low. These factors mainly included low oil prices and absence of appropriate infrastructure for processing or utilization as a feedstock. Several numbers of plants were operational during the 1990s, but they disappeared after a few years' operation (Raja & Murali 2011).

In recent years, the fluctuating price of oil has urged the researchers to explore new eco-friendly and economically favourable energy/ fuels from waste. USA and Europe encourage their people through government funding to develop projects from lab scale to pilot scale using biomass as a feedstock instead of non-biogenic waste materials. In China and India, scientific community is energized to search new ways to utilize waste plastics after knowing its potential benefits. European countries are facilitating their people to produce energy from waste plastic as a renewable source of energy ('biogenic'), as they are producing energy from biomass, the techniques and methods are used for this purpose are similar with slight modifications (Ambat et al. 2018). There are different procedures for biodiesel production depending on the feedstock type, which are listed below.

2.4. Pyrolysis

In 1990s, paraffin and crude oil was synthesized by direct heating of plastic wastes using pyrolysis. Thousands of elementary reactions are involved in pyrolysis and results in hundreds of volatile species. Generally, pyrolysis is the process of thermal decomposition of the material in the absence of oxygen. Pyrolysis, also termed as thermolysis (Alla & Ali ; Rana 2012), is a process in which feedstock is thermally (temperatures around 450–500°C) decomposed under an inert environment (N_2 gas). The formation of liquid fuel from plastics not only depends on their pyrolysis conditions but condensation of subsequent hydrocarbons as well (Saxena et al. ; Pütün et al. 2008). Pyrolysis is quite different from combustion and hydrolysis because it occurs in the absence of oxygen/ water (Bridgwater et al. 1999). The product contains liquid fuel, gas contents, and solid char. The process of synthesis of WPF from waste plastic includes the following steps as shown in Figure-2.2.

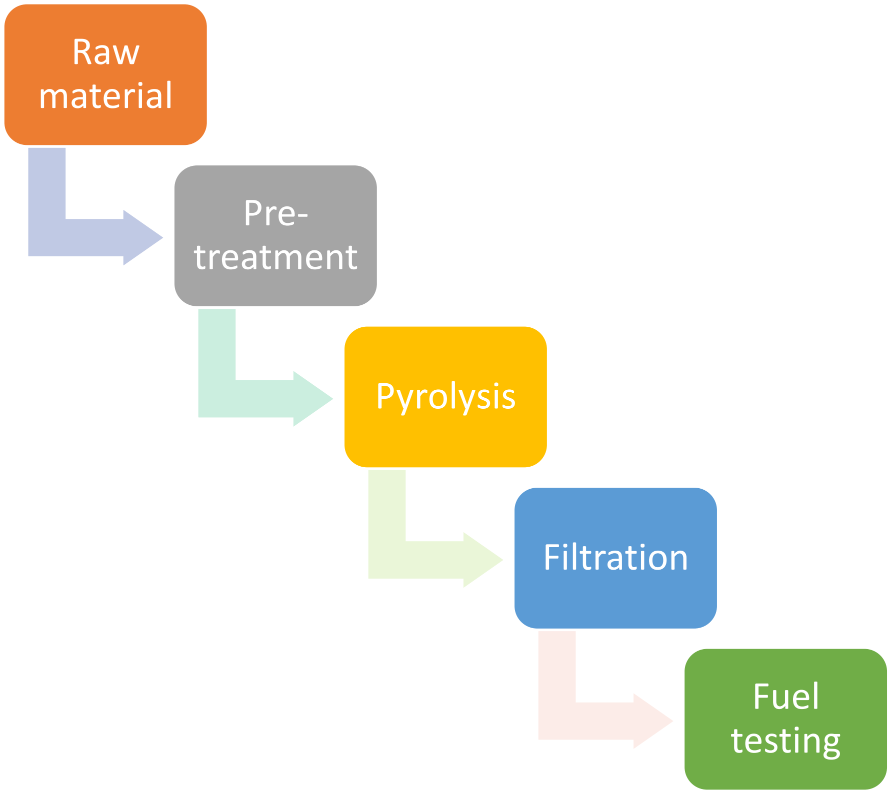

Figure-2.2. The process flow chart of fuel production from pyrolysis (AADHIK et al. 2016)

Different pyrolysis techniques, properties of biomass, and reaction conditions will result different concentrations of described products. Numerous techniques can be applied for pyrolysis such as circulating fluid beds, multiple hearth reactors, entrained flow reactors, and vortex reactors. Pyrolysis can also be carried out in the presence of a catalyst (Jahirul et al. 2012). The products of a pyrolysis process are shown in the Figure-2.3.

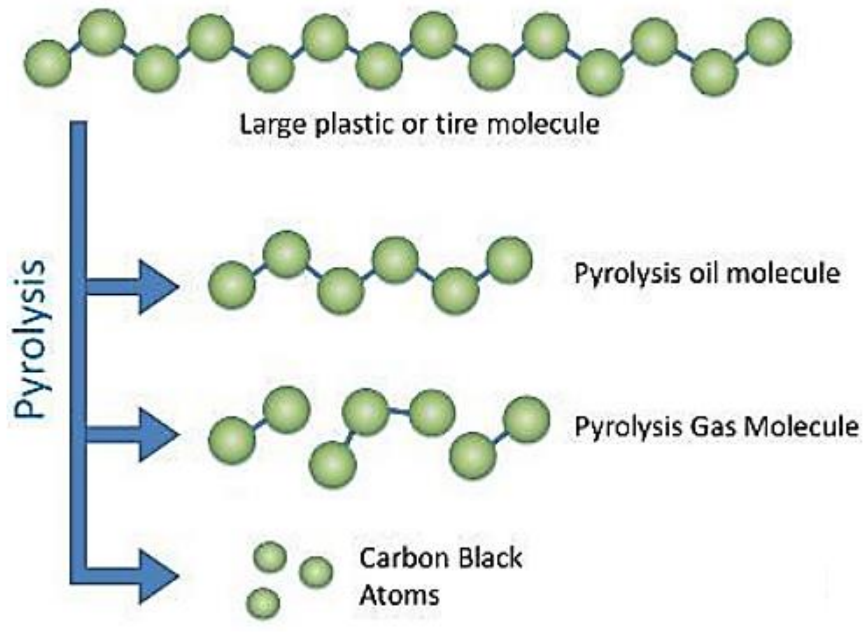

Figure-2.3. Pyrolysis process outcomes (Henan Doing Mechanical equipment Co.)

Different pyrolytic conditions yield different products. For example (Henan Doing Mechanical equipment Co.),

- **Slow pyrolysis:** In slow pyrolysis the feedstock residence time is >1 h and results in majority of solid product (i.e., char).
- **Fast pyrolysis:** In fast pyrolysis, the feedstock residence time is of few seconds and results in majority of liquid product (i.e., bio-oil).
- **Flash Pyrolysis:** Flash pyrolysis occurs at rapid rates at temperatures 400 and 600 °C with <1s duration for vapour habitation. In contrast to slow pyrolysis, it produces low quantity of gas and tar.

2.4.1. Feedstock

The appropriate plastic feedstock is decomposed in a reactor at 450-550 ºC. The feedstock contains PP, HDPE, LDPE and mixed plastic waste. In the reactor, a layer of carbonaceous material is gradually formed which depends on type of feedstock plastic and pyrolysis conditions. To ensure better heat conduction, this layer must be removed after pyrolysis.

The first stage, in feedstock preparation, is to dry the plastic waste if it contains water contents followed by its introduction into the reactor by using conveyer systems, as shown in Figure-2.4.

Figure-2.4. Feedstock preparation steps (plastic2oil.com 2019)

2.4.2. Feeding methods

The feeding methods to the reactor vary with the type of feedstock plastic. The simplest method is to feed the reactor without any pre-treatment. Shredder and a melter are used to treat soft plastics prior to their introduction into the reactor to reduce their volumes.

2.4.3. Types of reactor

Different types of reactors (e.g. kiln-type and screw-type) are being used along with electric power heating instead of burner. Moreover, a screw conveyor is present in the reactor on bottom side to remove it. One should have the expertise to run the plant and must have knowledge about procedure's operating conditions to save energy and minimize capital cost because these are the important parameters to evaluate plant performance. Furthermore, as the fuels are flammable, so the operator should take safety considerations foremost.

In a research study, WPF was commercially synthesised and used in a diesel engine. The whole process is illustrated in the Figure-2.5. The pyrolysis was conducted in a moveable semi-batch type reactor. The gases produced during the process were transferred to the alumina-based catalytic reformer due to the developed pressure gradient. An oil burner was provided at the bottom of reactor for providing heat for the thermal decomposition by maintaining temperature at 400°C. The catalytic reformer was used to process the produced gases followed by their scrubbing (oil is sprayed). The oil was received in the oil receiver and an incinerator was used for complete burning of residual gases. The new reactor (filled with feedstock) was installed upon completing pyrolysis reaction via an overhead crane (Lee et al. 2015).

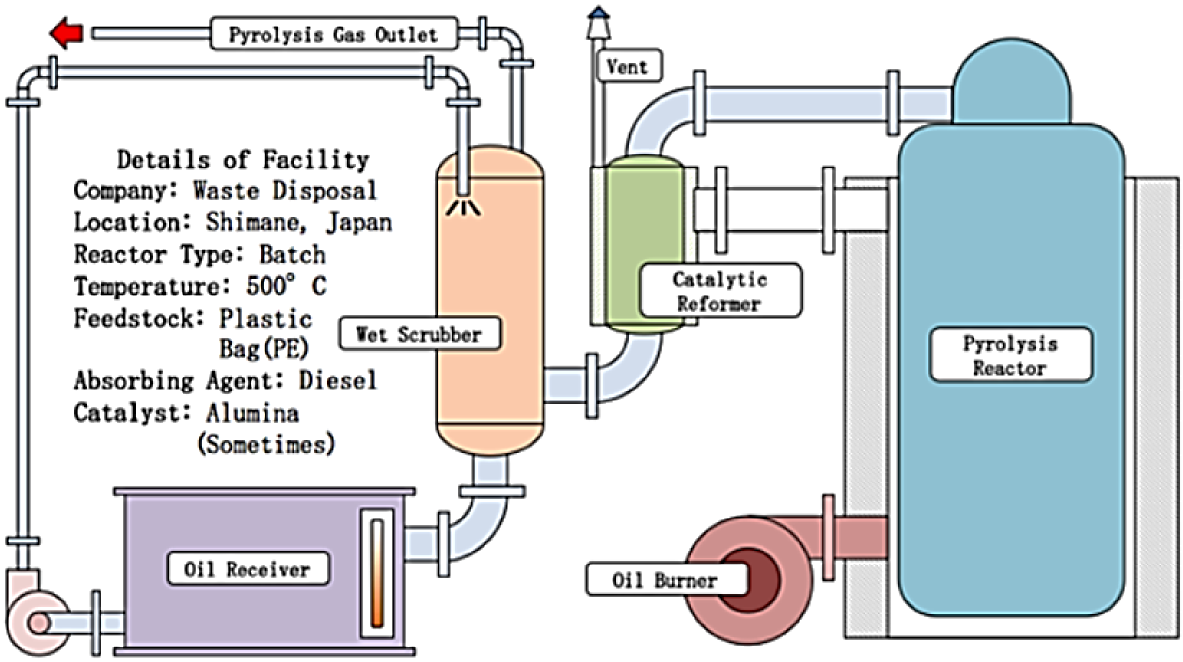

Figure-2.5. Commercially synthesis procedure of PPO (Lee et al. 2015)

Recently, Beston Technologies has introduced a pyrolysis plant for converting waste plastic to WPF (shown in Figure-2.6). Waste plastics are disposed through an advance version of conventional pyrolysis. The plant not only produces liquid oil, but carbon black as well. The five steps involved in the plastic pyrolysis process are explained as follow (Beston (Henan) Machinery and Co. 2019):

- First, feedstock is injected in pyrolysis reactor followed by heating the reactor by burning coal, or wood, or natural gas, oil. The slow heating of the reactor results oil gas at 250°C,
- The produced oil is processed followed by its cooling to get liquid oil. The non-condensed gas is recycled to combustion system that is used to heat the reactor instead of burning materials, which makes this process energy efficient and eco-friendly.

- Carbon black is removed automatically upon cooling the reactor to 40℃. Lastly, the exhausted smoke is treated prior to vent to achieve national emission standard through the advanced dedusting system.

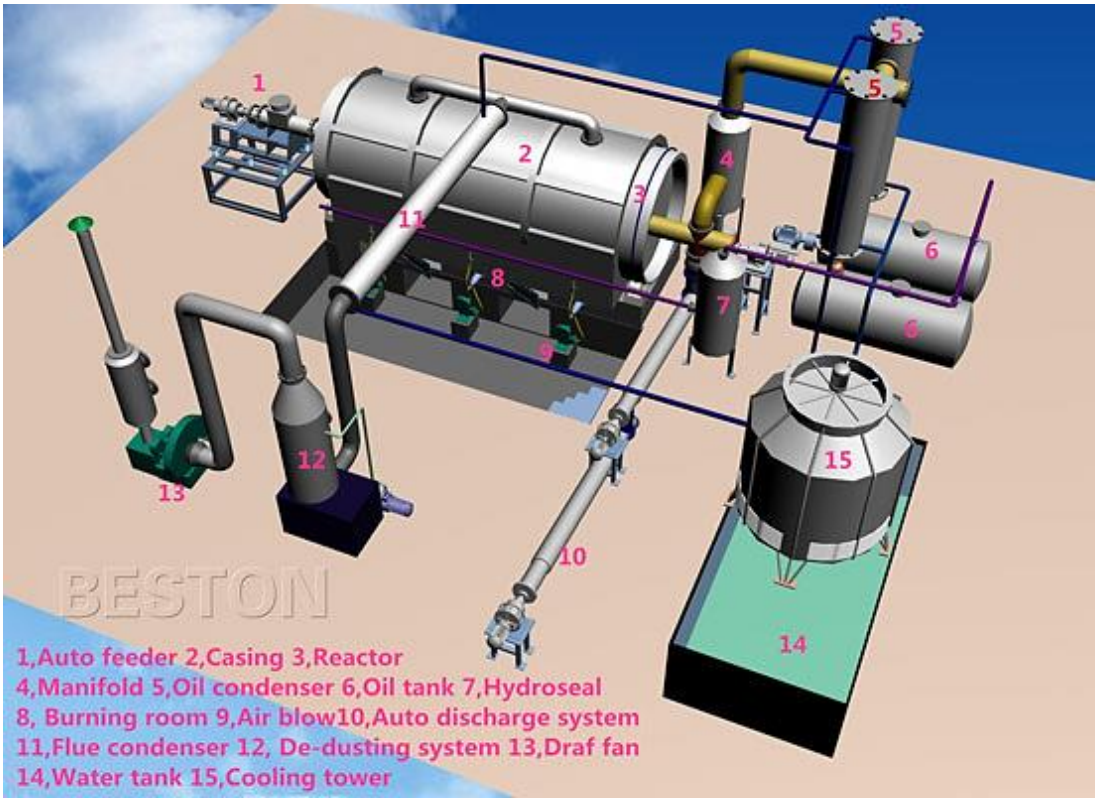

Figure-2.6. Beston WPF & gas production Plant (Beston (Henan) Machinery and Co. 2019)

2.4.4. Reactor products

The reactor products contain some high boiling point substances including diesel, kerosene and gasoline that are condensed in respective condensers. The uncondensed gases i.e. CH_4, C_2H_6, C_3H_8 and C_4H_{10} are moved to a flash stack. A number of properties and characteristics of liquid oils synthesized from different plastics are described in Table 2-3. The oils produced from HDPE, PP, and PS exhibited more than 40MJ/kg experimental calorific value, which is nearly similar to commercial transportation fuels. This signifies the fact that these oil can also be utilised in energy intensive works, such as automotive fuels (Onwudili et al. 2009).

Table 2-3. Characteristics of synthesized waste plastic oil (Sharuddin et al. 2018)

Properties	**Types of Plastics (experimental values)**						**Commercial Standard (ASTM 1979)**	
	HDPE	LDPE	PP	PS	PET	PVC	Gasoline	Diesel
Density @ 15°C (g/cm^3)	0.89	0.78	0.86	0.85	0.90	0.84	0.780	0.80
Viscosity (mm^2/s)	5.08 (40°C)	5.56 (25°C)	4.09 (40°C)	1.4 (50°C)	-	6.36 (30°C)	1.17 (40°C)	1.9-4.1 (40°C)
Calorific Value (MJ/kg)	40.5	39.5	40.8	43	28.2	21.1	42.5	43
Flash Point (°C)	48	41	30	26.1	-	40	42	52

2.4.5. Effect of temperature and pressure

Olufemi and Olagboye (2017), synthesized liquid fuel oil from waste plastics (including LDPE, HDPE, PP, other plastics) in a batch reactor at temperatures ranging 170 – 300°C under atmospheric pressure and characterized the obtained products. The effect of temperatures on liquid fuel production is represented in Figure-2.7. As the reactor's temperature reached its maximum (i.e. 300°C) the solid feedstock transformed into liquid and vapour products. The components of solid feedstock, such as PP, LDPE, HDPE and other plastics, had different transformation temperatures as 225°C, 210°C, 213°C and 197°C respectively. Similarly, their reaction periods were 210, 230, 220 and 260 minutes. The decomposition at different temperatures yield different long chain compounds, such as waste plastic grocery bags at 420 - 440°C yielded 74% crude oil. The results showed that increase in temperature increases the yield of gases and liquid products having low boiling points because oxygen reacts with organic compounds at the end of reactions yielding high percentage of liquid oil.

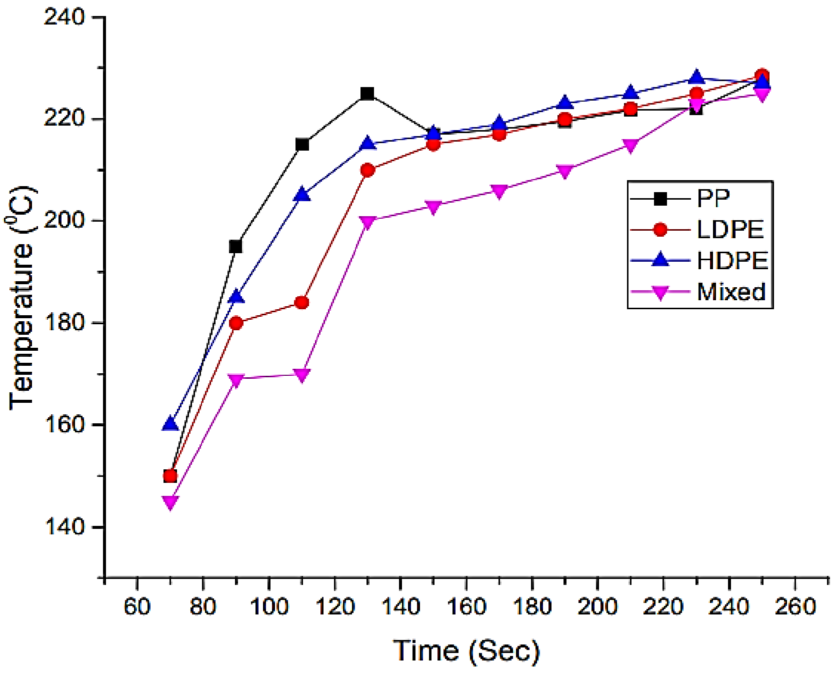

Figure-2.7. Temperature effect on oil production (Olufemi & Olagboye 2017)

Pressure also plays a key role in the production of oil products via pyrolysis. Higher pressure results in enhanced boiling points and cause heavy hydrocarbons to further pyrolysis instead of vaporizing at the provided temperature. Furthermore, highly pressurized conditions not only give high yield non-condensable gases, but reduce liquid products as well. But pressure has limited effect on C=C of the liquid product (Sharuddin et al. 2018).

2.4.6. Use of catalyst

Plastic pyrolysis reactions are optimized to attain the specific products through appropriate catalyst. Generally, hydrocarbons from C1 to C24 are present in petroleum fuels while straight hydrocarbons from C1 up to C80 are present in polyethylene pyrolysis products. Catalysts convert long carbon chains to short which also results in low boiling point products (AADHIK et al. 2016). The catalysts are only applied in pyrolysis of polyethylene as compared to polypropylene and polystyrene because they contain light hydrocarbons, which are comparable to commercial fuels. Some task specific catalysts are used to decrease unsaturated hydrocarbons and enhance stability and cetane number by yielding aromatics and naphthenes (Pinto et al. 1999).

Lewis acids such as $AlCl_3$ is used as a catalyst, some other catalysts are zeolites, gallosilicates, aluminium pillared clays, mesostructured catalysts, superacid solids, metals supported on carbon, and basic oxides, conventional acid solids (Anuar Sharuddin et al. 2016).

2.4.7. Filtration and purification

The produced oil will have certain impurities like wax, grease. To enhance purity, it should be cleaned. The purification can be performed either by gravity or by using any filter medium.

Gravity-based separation: The basic process of purification is via gravitation separation. The process includes a funnel like container in which the oil is poured and the concentrated liquid will settle down (water) with top layer above water is of wax and grease like pale greenish yellow substance. The unwanted materials are excluded by opening the cyclone valve at the bottom. The product is then forwarded to further proceeding.

Filter paper-based filtration: The filter paper is used to colloidal molecules present in the product based on their molecular sizes. Therefore, the smaller mesh size filter paper will provide the high level of purity.

2.5. Fuel Testing and Analysis

Different characterization techniques can be applied to determine the characteristics of produced oil such as GC/MS, FTIR, calorific value, flash point, ash content, cloud point, density, viscosity and pour point (Khan et al. 2016b). These techniques are discussed in detail as follows,

2.5.1. Physiochemical analysis

Density & viscosity: Both of these are important parameters that need consideration for fuel selection. Various parameters effect the viscosity including conditions of pyrolysis reactions, operating parameters, feedstock type and operating temperature. The IP-50 procedure is followed to evaluate viscosity at 40°C

Flash point: Flash point also an important parameter to describe the hazardous characteristics of fuels. It is described as the minimum temperature required to vaporize or an ignitable mixture in air.

Fire point and pour point: The ability of a material to support combustion is assessed by fire point that is defined as the temperature that cause burning of fuel up to 5s subsequently from the ignition. Moreover, fire point is usually greater than flash point and may vary from 5–10 °C. The waste plastic fuel oil has the reported fire point of 20°C. On contrary, fuel's ability to work at minimum temperature is evaluated by pour point that is the temperature, upon cooling the fuel, ceases the fuel motion.

Calorific value: Calorific value is the key factor to analyse the efficiency of fuel. It is amount of energy released by unit mass of fuel on complete combustion.

Sulphur and ash content: Sulphur contents in fuels results in SO_x formation that can harm the surrounding by polluting the environment. Moreover, they also reduce catalytic conversion capacity that results in enhanced concentration of emissions of NO_x, CO, hydrocarbons, and VOCs. The non-combusted fuel residue is known as ash content.

Carbon residue: Burning of fuel causes deposition of carbonaceous solid residue on the surface of burning object i.e. burner, injection nozzle upon vaporisation of fuel constituents. The preference is given to that oil which result in lower residual amounts of carbon. (Khan et al. 2016b)

2.6. Engine Performance Characteristics of WPF

In a research study, Kalargaris et al. (2017a) synthesized WPF with the setup shown in Figure 8. The characteristics of the synthesized WPF are compared with the commercial diesel in Table 2-4. They pyrolysed LDPE and EVA at temperatures ranging from 700ºC and 900ºC. Furthermore, they investigated its properties such as combustion, working ability and emissions production, by using it in a four-cylinder diesel engine (shown in Figure-2.8). Their results attributed that engine can be operated solely on WPF. Moreover, engine's performance was good enough as it produced lower quantities of NOx and COx. However, the quantity of unburned hydrocarbons was considerably high. Therefore, they also used a blend of the synthesized WPF and commercially available diesel in 75% and 25 % respectively in diesel engine and investigated its performance characteristics.

Table 2-4. Comparison of synthesized WPF fuel and commercially available diesel

Characteristics	**WPF**	**Commercial Diesel**
Density @ 15°C (kg/l)	0.9	0.8
Viscosity @ 40 °C (cSt)	1.9	2.6
Aromatic content (%)	65	29
Acid number (mg KOH/g)	41	0
Heating value (MJ/kg)	38	43
Ash content (wt. %)	0.2	< 0.001

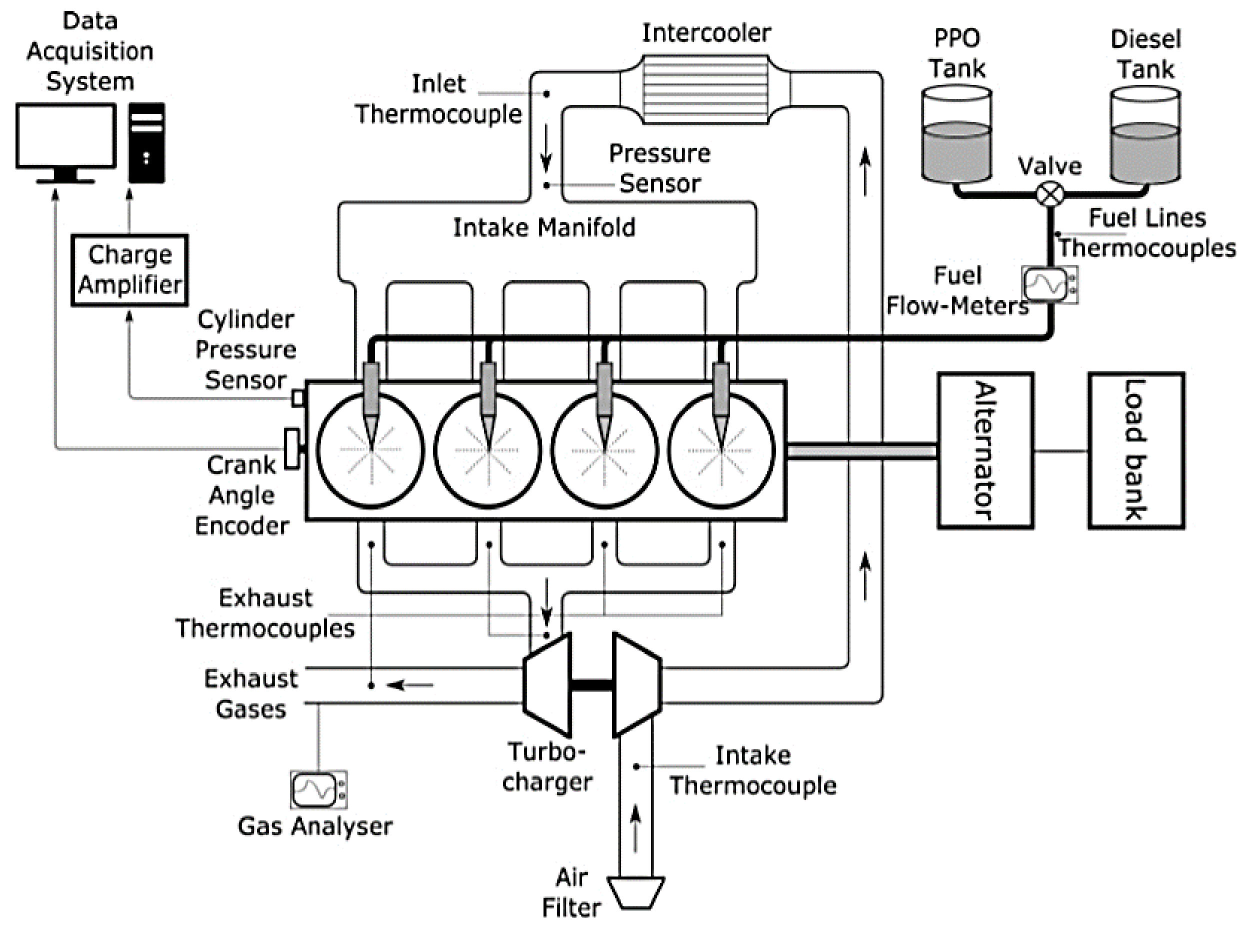

Figure-2.8. Schematic setup used by Kalargaris et al. for PPO production (Kalargaris et al. 2017b)

In another research study, WPF was commercially produced in a pyrolysis plant by utilizing household waste plastics. A small single cylinder air-cooled direct injection diesel engine was used for observing performance characteristics of WPF. Two blends of raw WPF and diesel fuel in 20% and 40% were also made and their performance was compared with the diesel fuel. The results exhibited that engine operation was much efficient at 20% blending ratio and the engine showed full load output, exhaust emissions and good thermal efficiency. A reduction of 13% and 17% was observed in engine power at intermediate engine speeds. The US EPA standard test modes were applied to examine the exhaust emissions with C1-8 and the

D2-5 mode for non-road vehicles and for generation sets respectively. The results showed that the exhaust emissions of NOx, THC, and CO were low during the operation. For 40% blending ratio, 37% and 57% reduction in engine power was observed at intermediate engine speed and rated engine speed (for few seconds), respectively. They proved that synthesized WPF can be used with a 20% blend irrespective of the engine speeds, however, blend of 40% could be applied below 2450 rpm engine speed (Lee et al. 2015).

Similarly, plastic oil was synthesized via thermal pyrolysis and utilized in a diesel engine as fuel. The results attributed that ignition delay duration was increased along with release of high amount of heat energy. Moreover, the results also exhibited the production of smoke and high quantity of unburnt hydrocarbons along with 25% high NOx production at peak loads (Mani et al. 2009). In another study, Nishida (1999) and co-workers have also obtained plastic oil by thermal pyrolysis and used it in marine diesel engines as fuel. It was found that NOx production (about 19%) was high, exhaust temperature was enhanced along with delayed ignition. The conventional heavy fuel oil used in marine engines produces high quantities of SOx, but its production was negligible with the usage of waste plastic oil.

ÖZCANLI (2013) also utilized thermal pyrolysis procedure to synthesize oil from waste plastics and attained high performance fuel via subsequent distillation. The results showed that, even with light oil, elevated amount of NOx were produced. Similarly, Kaimal and Vijayabalan (2015) used catalyst (silica) during pyrolysis of waste plastics to synthesize fuel oil. The blend of plastic oil and diesel was utilized in diesel engine to investigate the properties. The results observed include enhanced rate of heat release, high cylinder peak pressure and ignition delay at higher blending ratios.

Thahir et al. (2019) synthesised waste plastic oil by using PP in a fixed bed reactor along with refinery distillation bubble-cap plate-column under vacuum conditions (−3 mm H_2O). Vapours moved across the 4-tray distillation bubble-cap plate-column due to heat provided by reactor. The optimum temperature condition was found to be 580 °C at which 88 wt. percentage liquid oil was produced. Moreover, the process yielded five wt. percentage gas and seven wt. percentage char. Furthermore, it was observed that a temperature range of 500 - 560 °C yielded kerosene and gasoline in 60–67 wt. %. Nevertheless, at 600 - 650 °C, 64–83 wt. % diesel oil was produced. The thermal characteristics of the synthesized oil were similar to that of fossil fuels. In a similar way, Vijayabalan and Kaimal prepared liquid oil from waste plastics for generators via pyrolysis and compared their results with the commercially available diesel. The results are illustrated in Table 2-5. The results revealed that the synthesized oil from waste plastics has comparable properties to the regular diesel. Hence, it can be used as a replacement of regular diesel with some appropriate measures.

Table 2-5. Comparison of synthesized liquid oil and regular diesel (Vijayabalan & Kaimal)

Properties	**Waste Plastic Oil**	**Regular Diesel**
Density (kg/m^3)	793	850
Kinematic Viscosity @ 40°C (cst)	2.149	3.05
Calorific Value (kJ/Kg)	44200	42000
Cetane No.	50	55
Flash Point (°C)	40	50

Ash Content (%wt.)	0.002	0.045

2.7. Summary of the Research Findings

After an analysis of the previous research studies, it was concluded that majority of the studies only focused on the experimental evaluation of PDF and WPF. In most of the cases, these fuels have been studied individually along with other types of fuels or blends. In a research study, Mani et al. (2011) studied the engine performance characteristics of oil obtained from waste plastic in a direct injection diesel engine. These performance characteristics were compared with different blends of WPO-PDF and pure PDF. It was reported that the pure WPO exhibited high engine pressure, maximum heat release rate, and higher mean exhaust temperature. Moreover, the emissions (such as NOx, hydrocarbons) were also higher because of the high temperature of engine chamber as compared to the regular diesel or blends.

Similar findings were reported by Poompipatpong et al. (2014) in a study based on mathematical modelling (involving full-factorial design and ANOVA) of PDF-WPO blends. They studied the engine performance characteristics, such as engine torque, power output, fuel consumption, and thermal efficiency, of a heavy-duty diesel engine. It was found that blends having major proportion of WPO (e.g. 75%) resulted in 24% reduction of the engine torque and power output at different engine speeds. Similarly, the thermal efficiency was also found to be 6% lower and further investigation was recommended for successful utilisation of pure WPO.

In another comprehensive research study, Cleetus et al. (2013) synthesized oil through catalytic pyrolysis of waste plastic bags. This oil was used as a fuel in a diesel engine by making seven different blends with petroleum diesel and the performance, emissions characteristics were studied in detail. Overall, the WPO based engine performance was much inferior to the conventional petroleum diesel, as observed in previous studies as well. However, it was found that blends having higher concentration of regular diesel and lower concentration of WPO can exhibit promising results and WPO is a strong competitor in the area of alternative fuels.

In terms of computational analysis, a computational fluid dynamics (CFD) study was conducted by Govindan et al. (2014) involving analysis of the effect of blending ratio on combustion characteristics in compression ignition engine by using blends of regular diesel with biodiesel obtained from Thumba oil, in ANSYS software. Similarly, Taib et al. (2018) conducted simulation studies of diesel-ethanol-palm methyl ester blends on a Yanmar TF90 diesel engine and studied performance characteristics. In these studies, the engine performance characteristics obtained by using different blends were similar to the regular diesel. Moreover, the blends having lower concentrations of biodiesel (less than 20% in a blend) showed better results as compared to the other blends.

None of the research studies reviewed during the organisation of this literature review reported the modelling simulation of a four-stroke diesel engine (such as Yanmar L48N) utilizing only WPF. Majority of the studies have investigated the experimental implications of WPF-PDF blends as fuels and the numerical analysis of engine performance, emission characteristics was not found. Considering this, a novel approach was adopted to study the experimental results of PDF and compare them with the simulation results of WPF obtained by using ANSYS 19.2 software.

CHAPTER 3. PROJECT METHODOLOGY

3.1. Introduction

The methodology of this project is elaborated in the Figure-3.1. As sown in the figure, the first stage involved the analysis of petroleum diesel fuel (PDF) at different engine speeds in Yanmar L48N6 engine. The selected engine speeds were based on the engine performance curves given in the appendices. The data for engine performance parameters, such as torque, power, exhaust temperature, and air-fuel ratio were obtained through three experimental runs. Similarly, data for gaseous emissions such as NOx, COx, and unburnt HC was also obtained in these runs. This data was arranged, analysed and compared through different graphical presentations, as given in the next chapter.

Same methodology was adopted for simulation studies on a single-cylinder 4-stroke vertical test engine having with engine parameters same as that of L48N6. The waste plastic oil (WPO) was used as a fuel in this test engine with three different rpm runs. The simulation performance parameters were torque, power, and exhaust temperature. On the other hand, only NOx emission data was obtained through simulation. These simulation parameters were selected for reducing the computational load and limiting the time spent in simulation studies.

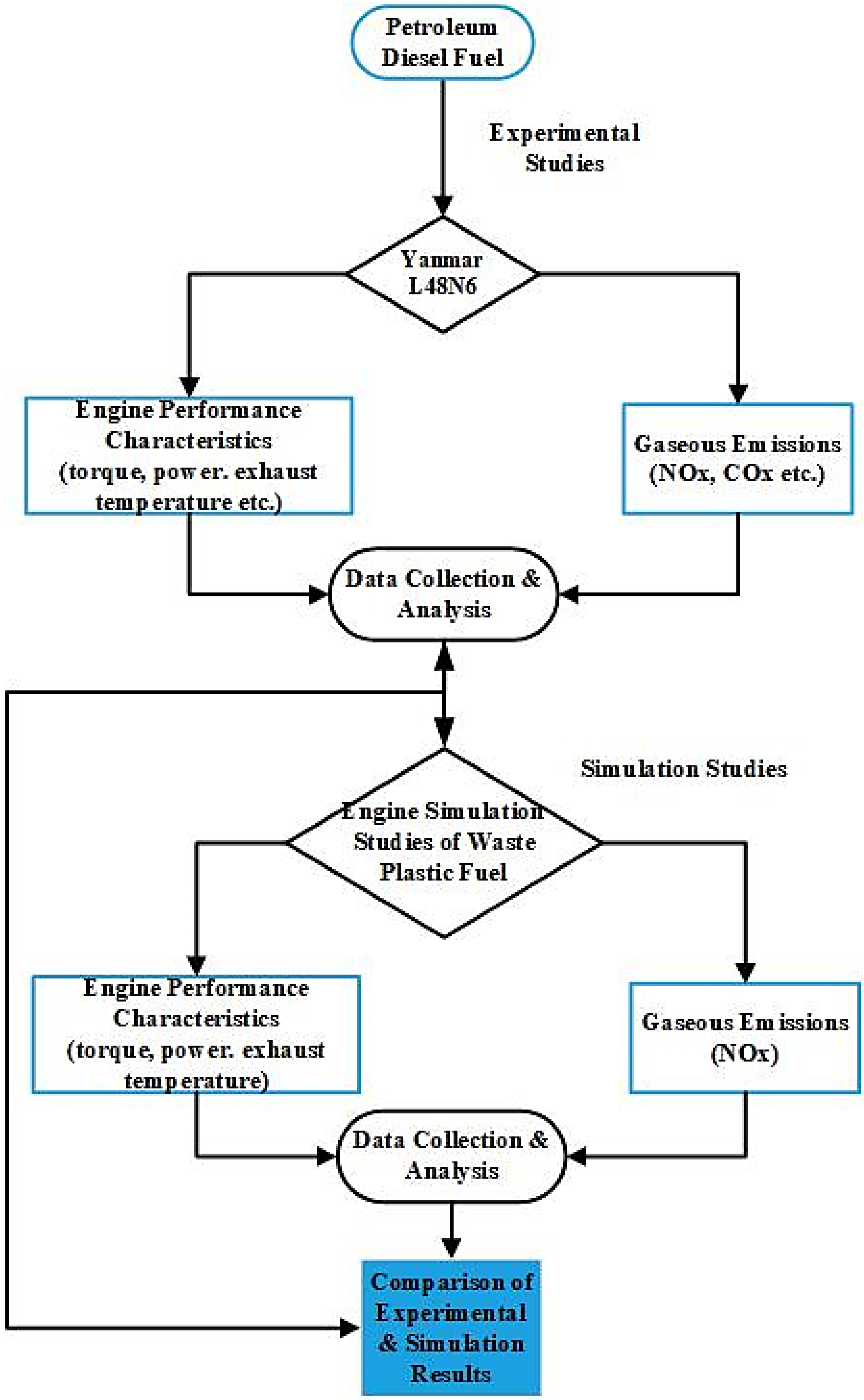

Figure-3.1. The different steps and stages in the methodology of this project

3.2. Engine Testing Parameters

A number of experiments were conducted for comparison of various parameters at different engine speeds. The types of fuel used in this study, engine speeds, and parameters studied are given in the Table 3-1. As evident, five engine speeds were selected for PDF experiments. The selection of these speeds was based on the rpm range (1400 to 3800 rpm) in the performance curves of L48N6 shown in the Appendix-B. On the other hand, three engine speeds were selected for simulation studies of WPF due to time constarints in computational analysis. Same approach was adopted for studying the simulation results of engine's key parameters.

Table 3-1. Types of fuels and parameters studied in this research

Types of Fuels	Engine Speeds (x ± 10 rpm)	Parameters Studied & Compared
PDF (Experimental Study)	1800 2000 2600 2900 3800	Torque Power Exhaust Temperature Air-Fuel ratio Nitrogen Oxides Carbon Oxides Unburnt Hydrocarbons
WPF (Simulation Study)	1800 2000 2600	Torque Power Exhaust Temperature Nitrogen Oxides

As shown in the solver setup parameters in the Appendix-C, the n-decane was used as surrogate for PDF for conducting the simulation runs in this study. During the review of existing literature, it was found that the composition of fuels obtained from waste plastics can vary considerably and no standard composition was available. A research study conducted by Mani et al. (2011) was selected for deciding the composition of WPF used in the simulation. According to them, the major component of WPF is C10 compounds and their concentration could be as high as 60%. So therefore, n-decane was selected as a surrogate for WPF.

3.3. Engine Setup

The experimental studies were carried out on an engine-testing stand having Yanmar L48N engine. A number of characteristics of this engine are given in the Appendix-B and an actual image of the experimental stand is shown in the Figure-3.2. The testing stand is composed of a dynamometer connected to engine, an exhaust gas analyses system, and a complete set of instrumentation. Information such as fuel consumption, pressure within cylinder during run, and composition of exhaust gas emissions can be collected. The different parts of the engine are listed as follows,

1) Engine
2) Dynamometer
3) Encoder
4) Load valve
5) Exhaust gas temperature
6) Airflow meter
7) Pressure transducer

8) Wideband lambda sensor

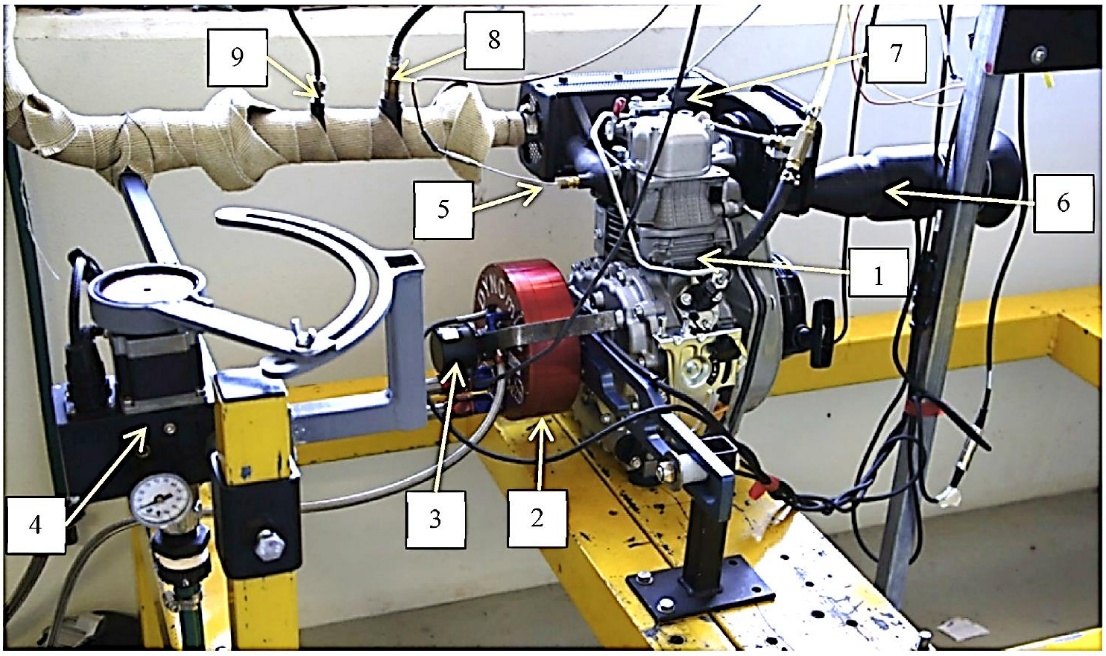

Figure-3.2. The engine test stand having Yanmar L48N6 engine available at USQ, adapted from Al-lwayzy and Yusaf (2017)

As mentioned previously, the selection of engine speeds was based on the engine's performance curves shown in the Appendix-B. These curves are based on a number of parameters such as fuel consumption, exhaust temperature, torque, power output, and smoke density. This data was obtained at room temperature, pressure and relative humidity of 30%.

3.4. Simulation & Validation Studies in ANSYS

The experimental results obtained from Yanmar L48N were compared with the numerical results obtained by simulating a test engine in the ANSYS software. The major steps followed in the simulation procedure are given by as follows,

3.4.1. Creation & Setup of an Analysis System

Initially, the ANSYS Workbench 19.2 interface was opened and the type of analysis (IC Engine-fluent) was selected from the list of analyses systems. The project was saved with an assigned name (IC-WPF-Validation), as shown in the Figure-3.3.

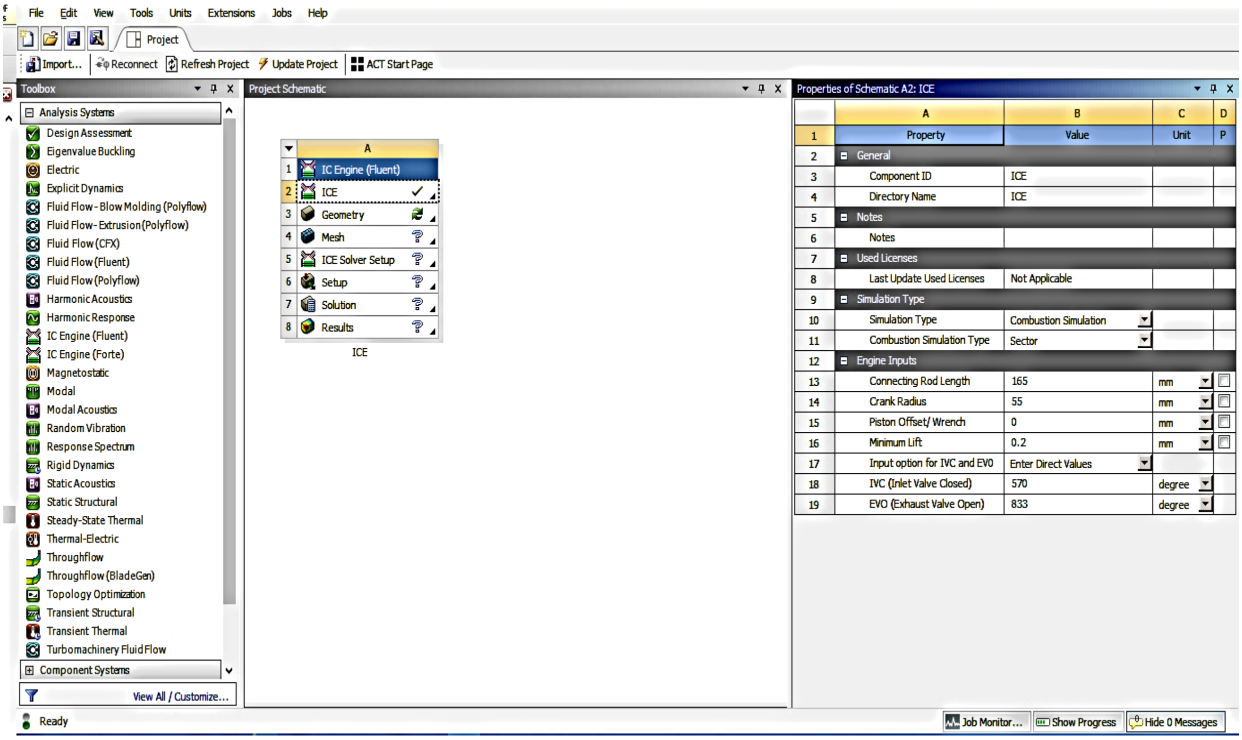

Figure-3.3. Workbench 19.2 interface

The information relating to the engine specifications and other parameters were added to the ICE tab. The simulation type was selected as combustion simulation. Moreover, among the three types, sector combustion simulation was selected for this study. The values for the different engine inputs are given in the Appendix-C.

3.4.2. Creation & Setup of Geometry

The next step was the creation of a decomposed geometry by using SpaceClaim or DesignModeler integrated with the ANSYS software. For simplifying the simulation stages, the geometry of a four-stroke diesel engine was obtained from ANSYS customer portal. The layout of the geometry created in DesignModeler is shown as follows,

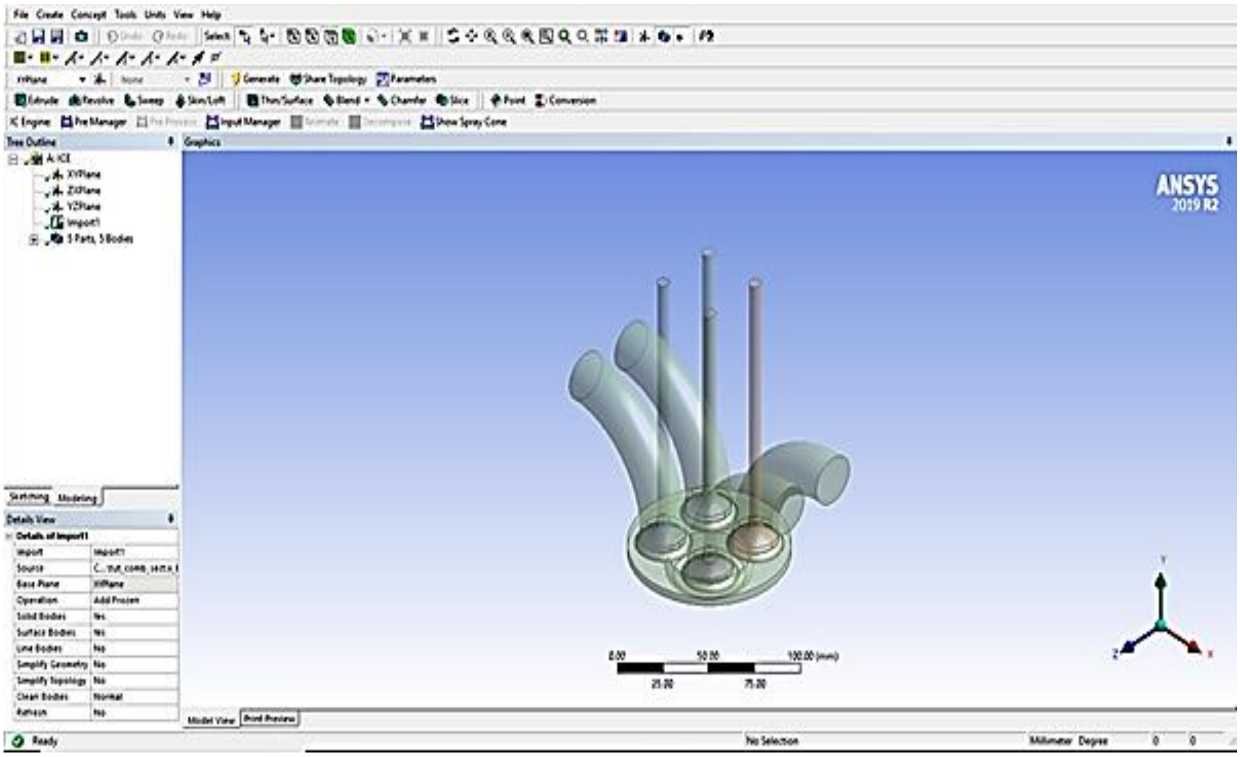

Figure-3.4. Test engine geometry before decomposition

The inputs required for decomposition were added to the input manager. The various inputs for the engine parameters and their respective values are shown in the following table.

Table 3-2. Engine parameters in simulation study

Input	Value
Sector Angle	45^0
Spray location Height	0.02 mm
Spray Location Radius	0.02 mm
Spray Angle	70^0
Compression Ratio	20.1

Once the values incorporated, the geometry was decomposed by pressing decomposition tab. During the decomposition a number of changes took place such as,

- Formation of a sector of engine cylinder
- Removal of inlet and exhaust valves
- Adjustment of crevice volume
- Piston is moved to appropriate position as per the decomposition crank angle

3.4.3. Generation of Sector Mesh

The next step was to generate a meshed geometry by using the integrated meshing software. The meshing stage is also an integrated step and the size/volume could be adjusted as per need. In our case, the inputs under the setup mesh tab, named as IC sector mesh parameters, were kept as default. Here, a 45° sector of the combustion chamber was studied for reducing the computational load and time required, similar to Ma et al. (2014). The meshed sector geometry is shown in the Figure-3.5.

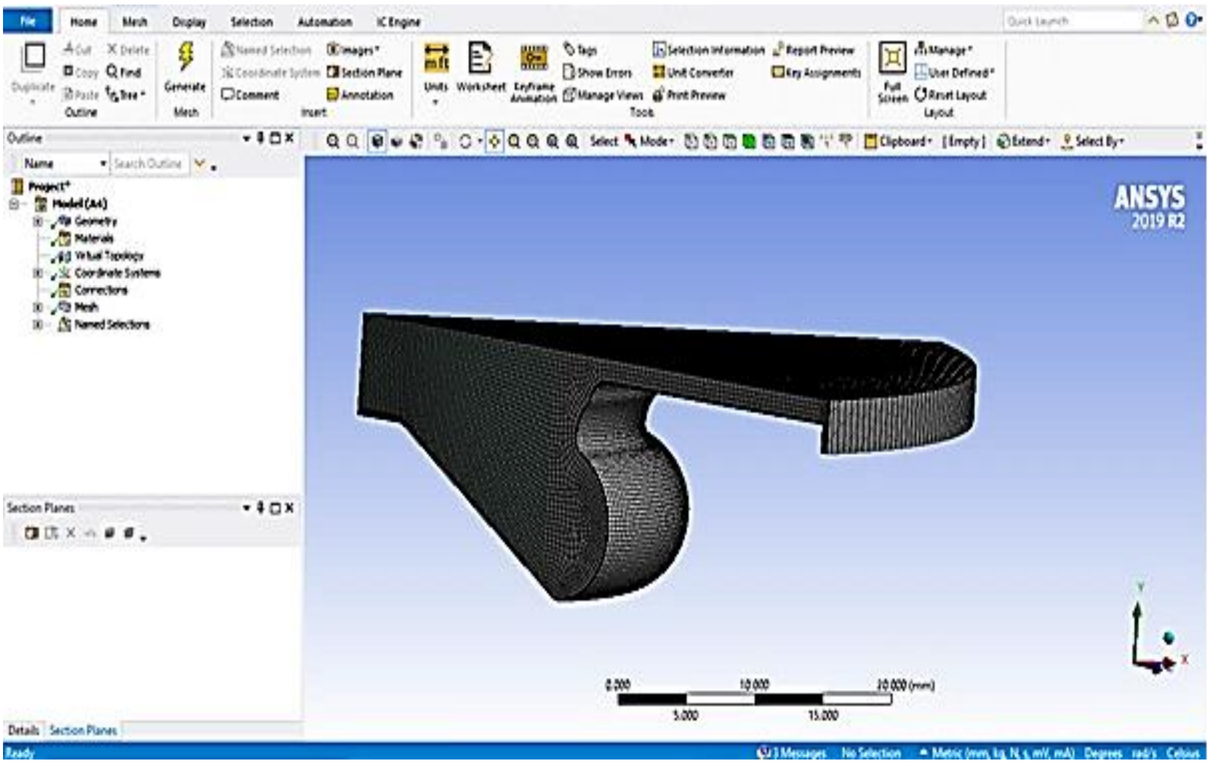

Figure-3.5. Generated sector mesh

3.4.4. Case Setup and Solvation

After the completion of sector mesh, the model was setup by adding the respective values to the ICE Solver Setup tab. The solver settings constituted various subsections such as,

- Basic Settings,
- Physics Settings,
- Boundary Conditions,
- Monitor Definitions,
- Initialisation

- Post-Processing.

The different values used in the subsections are given in a table in the Appendix-C. Once all of the values incorporated, the case was set up in ANSYS Fluent, as shown in the following Figure-3.6.

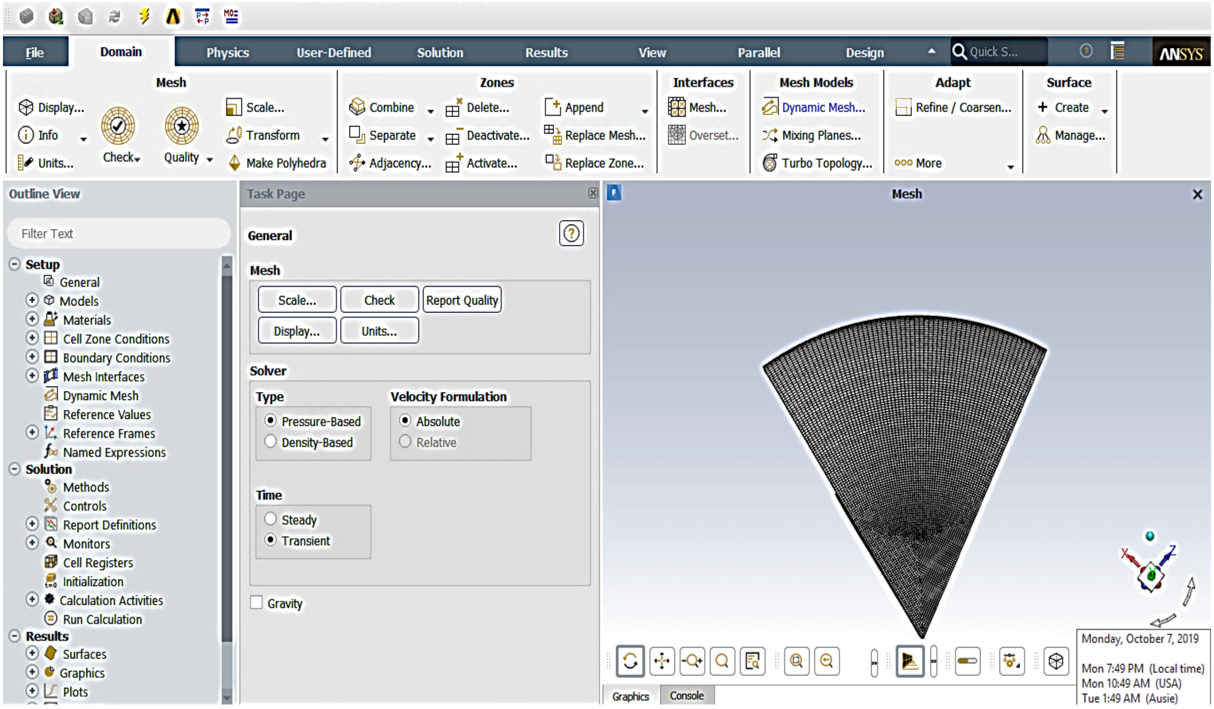

Figure-3.6. Case setup in Fluent interface

Before proceeding with the calculations, the quality of generated mesh was evaluated and all of the input parameters were re-checked. In the results section, a number of different contours were selected for visualising the results obtained at the end of calculation. Once everything setup, the calculation was initiated and results file were generated as a comprehensive HTML report.

CHAPTER 4. RESULTS PRESENTATION

4.1. Introduction

In this section, the experimental and simulation results obtained by studying the petroleum diesel fuel (PDF) and waste plastic fuel (WPF) in a diesel engine are presented in detail. Both types of results constitute the performance characteristics and emission values of the two fuels. The PDF was tested on Yanmar L48N6 by running the engine at five different speeds ranging from 1800 rpm to 3800 rpm. Among these speeds, first four were under load and the 3800 rpm was under no-load condition. The different trends in the experimental and simulation results obtained in this study are presented as graphs.

4.2. Experimental Results of Petroleum Diesel Fuel

4.2.1. Engine Torque and Power Output

The values of engine torque for the three different runs of PDF have been plotted in the Figure-4.1. As evident from the figure, the test engine exhibited a torque range of lowest 9.32 Nm to highest 11.20 Nm. The highest torque as obtained at 2600 rpm for all of the three runs. A comparison of the torque trends with the standard performance curves of the test engine reveals a clear similarity in the behaviours. In both cases, 2400-2800 rpm range translated to maximum engine torque.

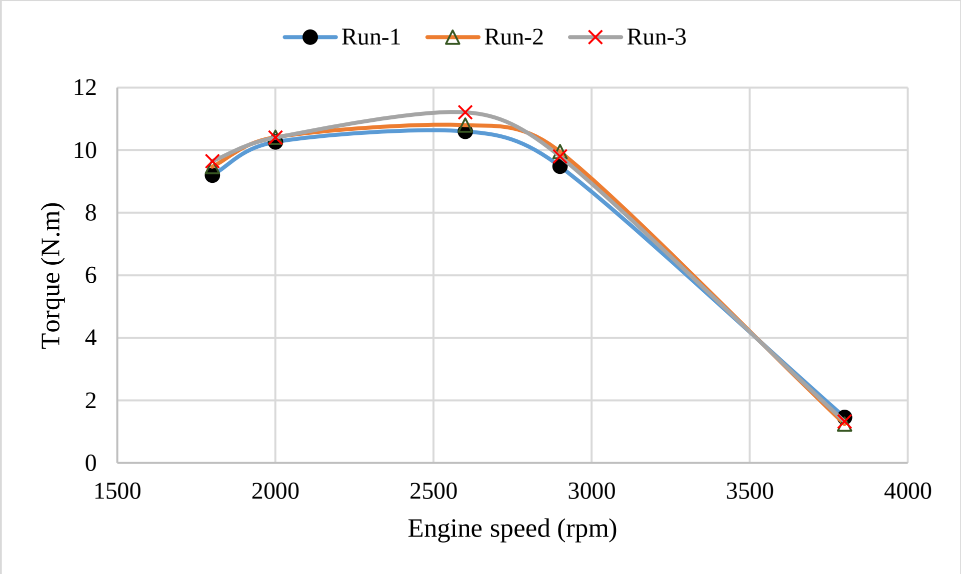

Figure-4.1. Engine speed versus torque for the three runs

This is a general characteristic of a diesel engine that an increment in engine speed leads to escalation of engine torque up to a certain rpm. This is mostly due to the friction losses during the operation and engine's inability to ingest a full air charge. Similar trend was observed for the case of engine power. The results for engine power output are shown in the Figure-4.2. The engine produced maximum power at 2600 rpms for all of the three runs and it was nearly 3.95 kW on average. Whereas, the lowest power output was observed at 3800 rpm under no load conditions. The power output at this rpm was only 0.71 kW for all of the three runs.

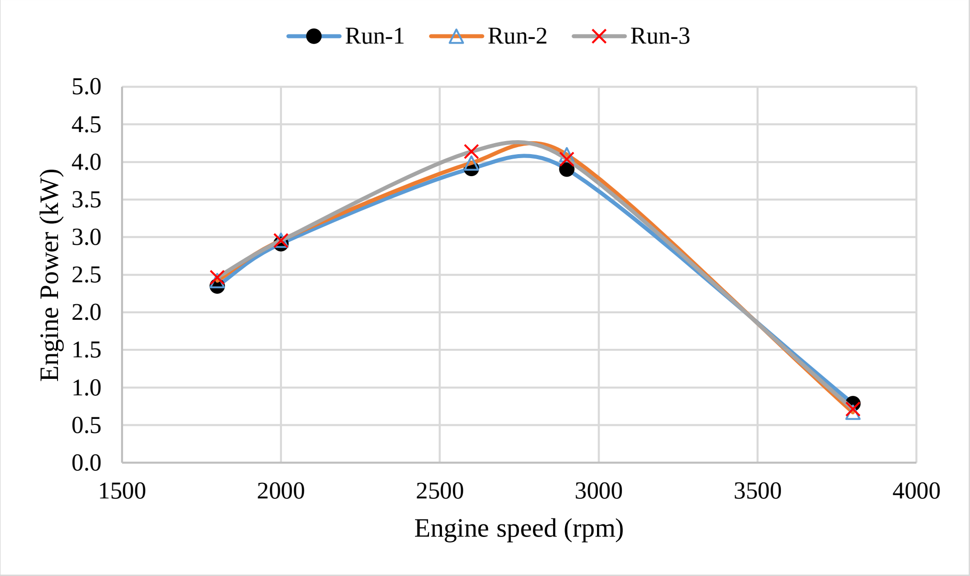

Figure-4.2. Engine speed versus power output for the three runs

4.2.2. Exhaust Temperature

During the experimental runs at different speeds, the temperatures of exhaust gases were obtained. The data obtained in three runs exhibited similar behaviour and is plotted on the same Figure-4.3. There was a uniform increase in the exhaust temperature with an increase in the engine speed. For all runs, the highest temperature of 516 K was observed at 2600 rpm and, beyond this speed, there was a slight decrease in exhaust gas temperature. This behaviour is in accordance with the standard engine performance curve shown previously. The lowest exhaust gas temperature was 260 K at 3800 rpm under no-load conditions.

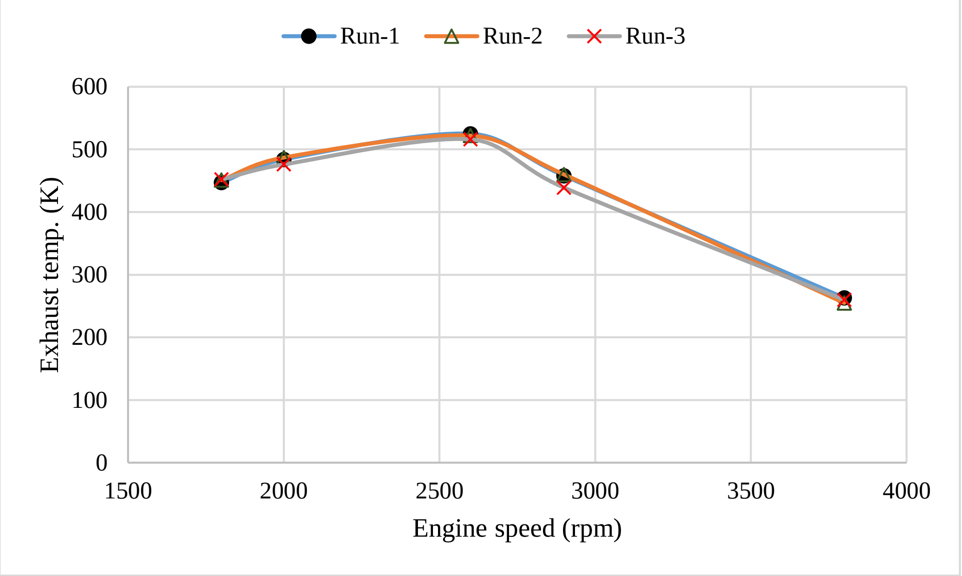

Figure-4.3. Engine speed versus exhaust temperature for the three runs

4.2.3. Air to Fuel ratio

The AFR values for the three runs are plotted on a graph shown in the Figure-4.4. As before, each dataset exhibited similar behaviour at different engine speeds. Initially, at 1800 RPM the AFR commenced at 18.66, is slightly decreased to 18.08 at 2000 rpm, and then it increased in a uniform manner. At 3800 rpm, the maximum value of AFR (53.87) was observed.

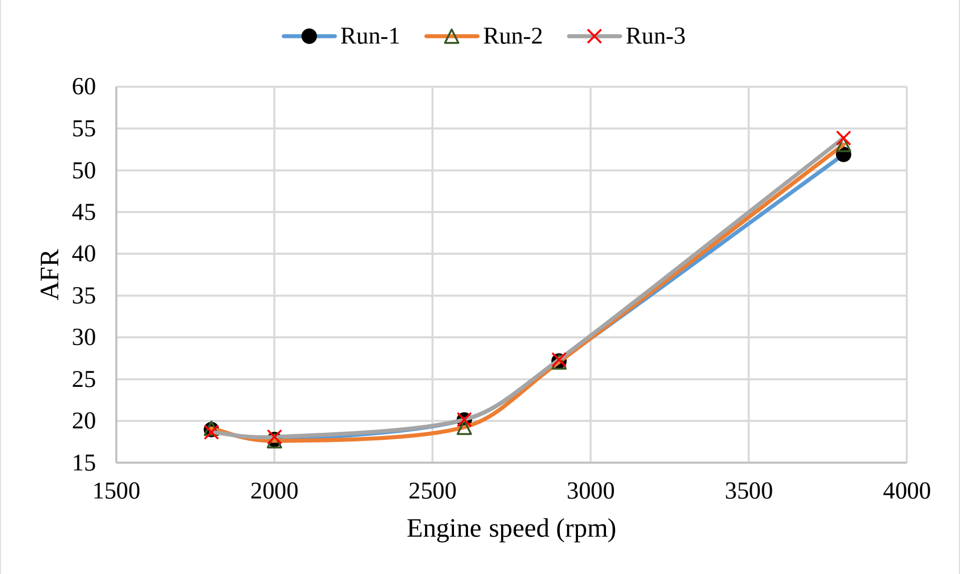

Figure-4.4. Engine speed versus AFR for the three runs

4.2.1. Emissions of NOx

Figure-4.5 displays the data obtained for NOx emissions for the three runs. In all cases, lower concentrations of oxides of nitrogen were observed in the rpm range of 1800 to 2600 rpm. The maximum concentration of NOx was found to be 596 ppm in run-1 at 2900 rpm. The other two runs also exhibited maximum concentration of NOx at the same rpm. As seen previously as well, the NOx production is dependent on the load applied to the engine. Under no load conditions at 3800 rpms, the production of NOx was minimum, just 154 ppm.

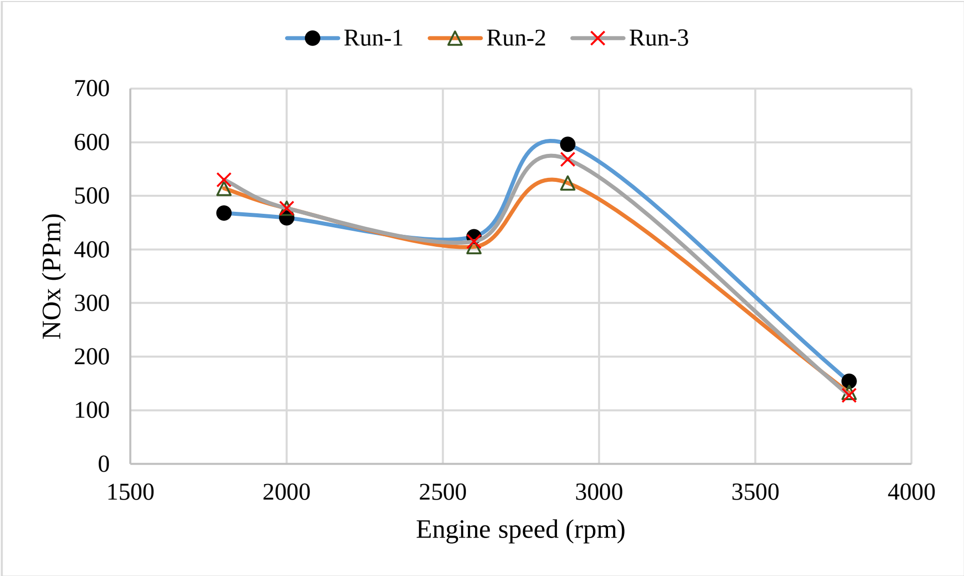

Figure-4.5. Engine speed versus NOx emissions for the three runs

4.2.2. Emissions of Carbon Oxides

The emissions of two of the oxides of carbon (CO and CO_2) were studied and the obtained results are plotted in the Figure-4.6 and Figure-4.7, respectively.

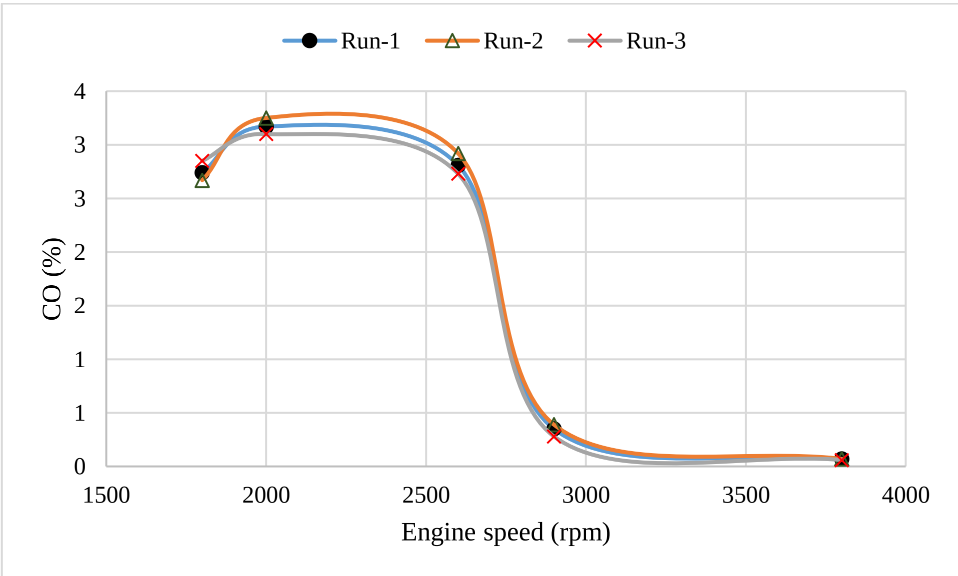

Figure-4.6. Engine speed versus CO emissions for the three runs

Here, maximum emissions of carbon oxides were observed at 2000 rpm. As compared with the results, the behaviour of omissions was not well defined with the variation of engine speeds. Whereas, in case of carbon dioxide, all of the three runs exhibited similarity in the emission trends.

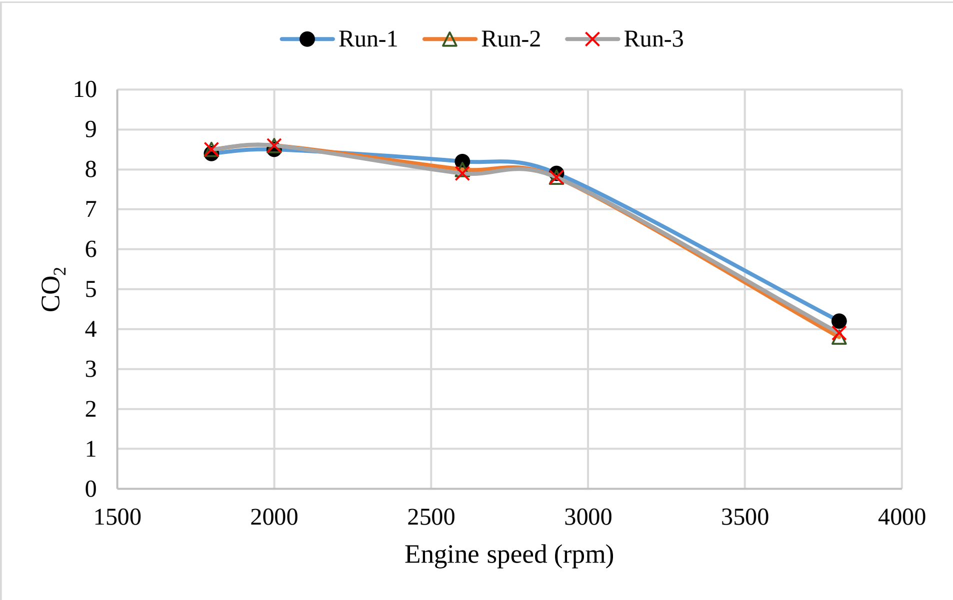

Figure-4.7. Engine speed versus CO_2 emissions for the three runs)

4.2.3. Emissions of Unburnt Hydrocarbons

As observed previously in the case of carbon oxides emissions. The emission trends of hydrocarbons by the three fuels were not well defined, as shown in the Figure-4.8. The maximum emissions of hydrocarbons were found to be 92 ppm in the first run at 2000 rpm. The rest of two runs also gave similar results at 2000 rpm with a slight difference (1 or 2%) in the emissions.

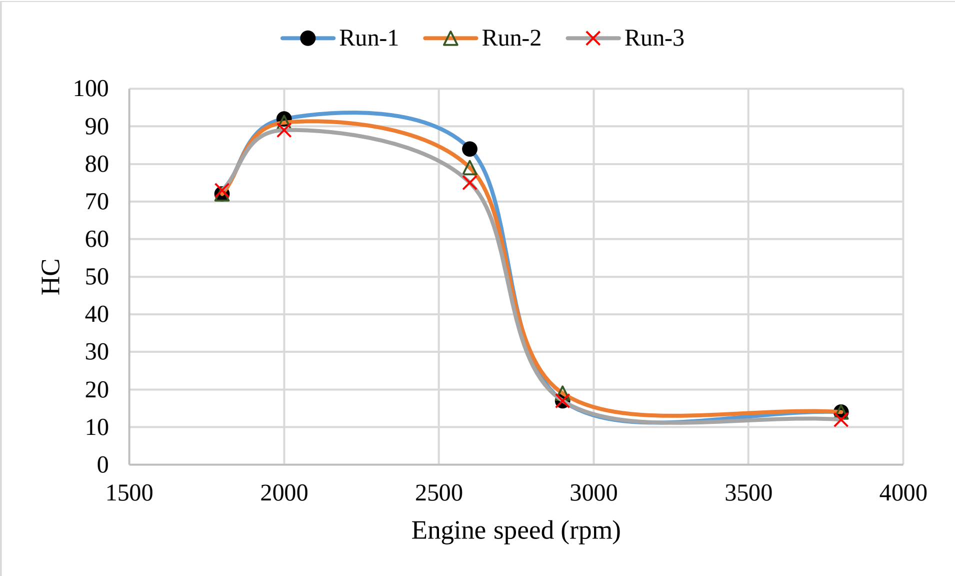

Figure-4.8. Engine speed versus hydrocarbon emissions for the three runs

4.3. Simulation Results of Waste Plastic Fuel

4.3.1. Engine Torque and Power Output

The values of engine torque and power output obtained through simulation runs are shown in the Figure-4.9 and Figure-4.10. In both cases, engine torque and power increased proportionally with increasing revolutions. Here, the torque ranged from 3.25 Nm to 12.5 Nm and power output ranged from 0.83 to 4.6 kW at the lowest and highest rpms respectively. The obtained trends are further discussed and compared with the experimental PDF runs in the next chapter.

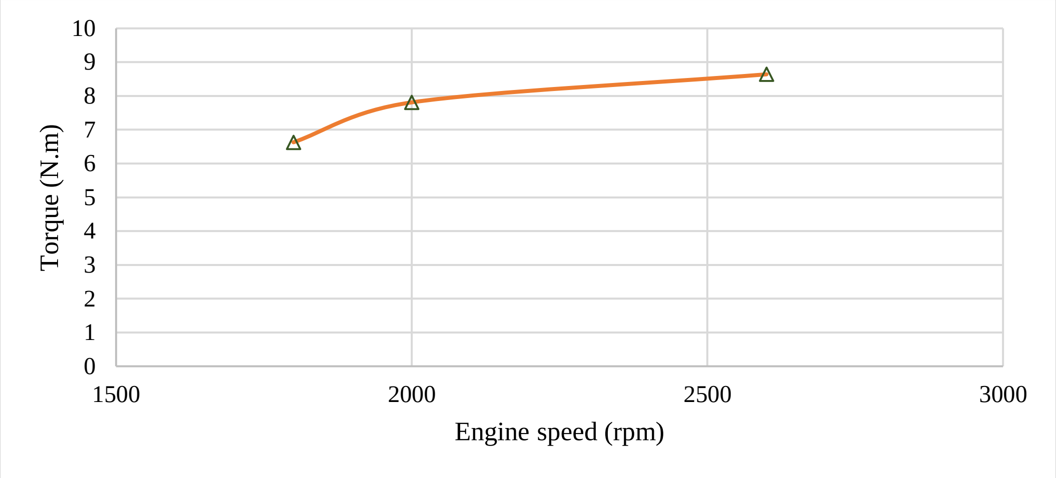

Figure-4.9. Simulation results of engine torque

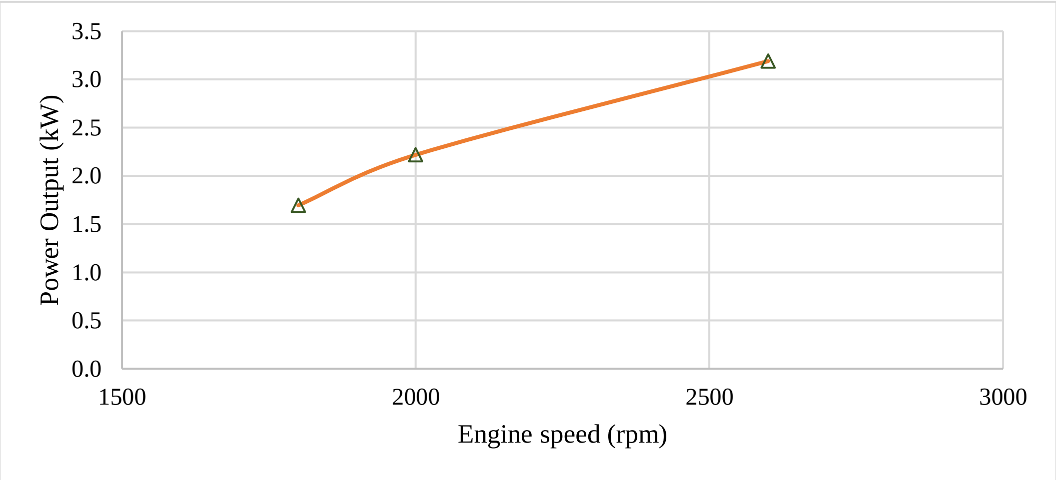

Figure-4.10. Simulation results of power output from the test engine

4.3.2. Exhaust Temperature

Figure-4.11 displays the simulation results of exhaust temperatures at various engine speeds. As before in experimental results, simulation exhaust temperatures also increased from 1800 rpm to 2600 rpm. However, the simulation temperature was 8% higher than the experimental temperature at all speeds.

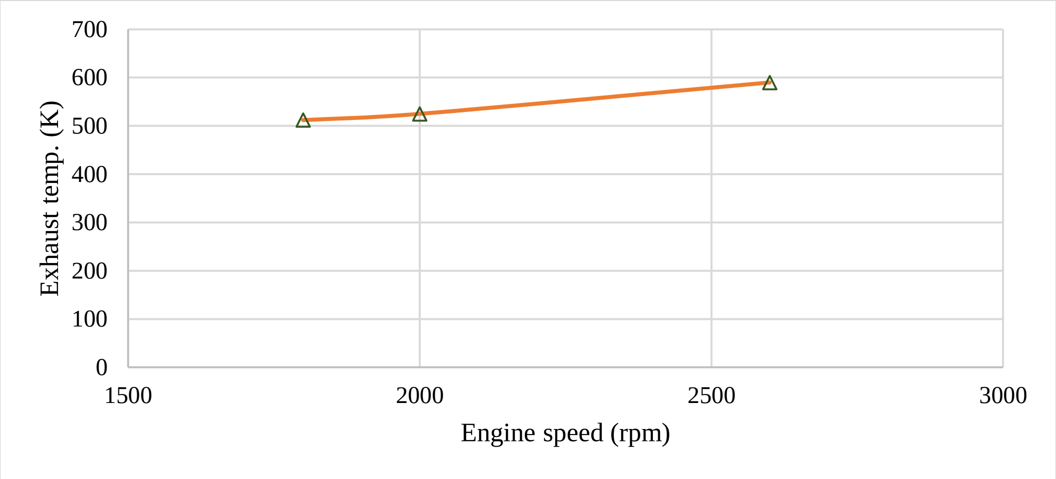

Figure-4.11. Simulation results of exhaust temperature

4.3.3. Emissions of NOx

The simulation results of NOx emissions at the three engine speeds are shown in the Figure-4.12. At the lowest rpm, the simulation NOx was 780 ppm. Whereas, at higher engine speeds, it decreased gradually to nearly 500 ppm.

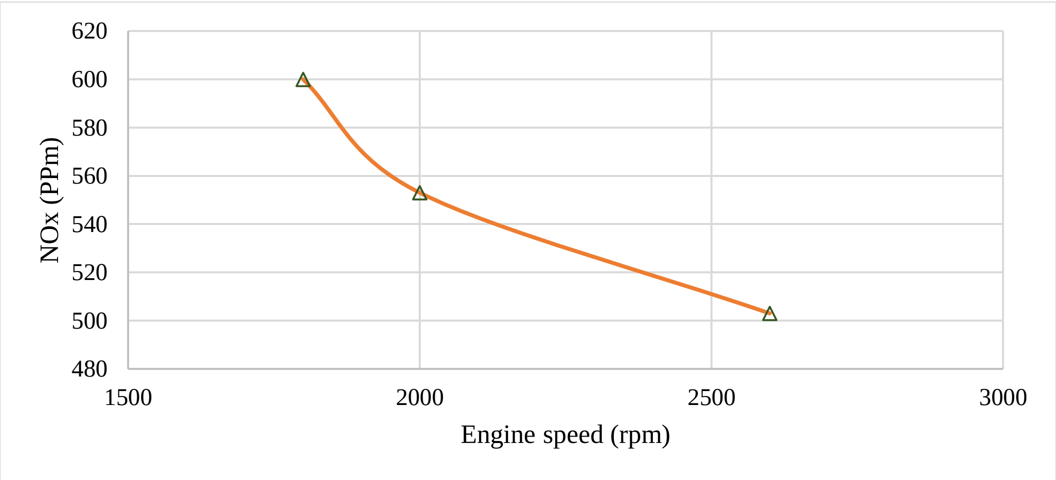

Figure-4.12. Simulation results of NOx emissions

4.1. Summary

In this section, all of the data (either experimental or simulation) was presented as x-y scatter graphs for analysing the obtained trends. Both types of fuels exhibited considerable performance and emission data forming the basis for comparison. As mentioned previously, the PDF was tested on engine at five different speeds ranging from 1800 to 3800 rpm. For all experimental performance data, 2600 rpm exhibited the maxima of torque (~11.20 Nm), power output (~4.14 kW), and exhaust temperature (517 K). Similar trends were observed for simulation runs, and the maximum value of each parameter was obtained at 2600 rpm, as shown previously. However, the emissions trends were scattered around different rpms and no specific behaviour was observed for each emission at specific rpms. For example, NOx emissions were found to be maximum at 2900 rpm, whereas, the emissions of carbon oxides and unburnt hydrocarbons were maximum at 2000 rpm. An effort was made to further understand and explore such behaviour in next sections and probable reasons were identified.

CHAPTER 5. DISCUSSIONS ON RESULTS

5.1. Introduction

The numerical modelling is mathematical description of a physical system or process in the real world. Its development involves a number of steps/parameters such as partial differential equations, initial/boundary conditions, related equations and solving methods. As shown in the Figure-5.1, the purpose of numerical modelling is to compare with the real-life circumstances or experimental observations (Oberkampf 2001).

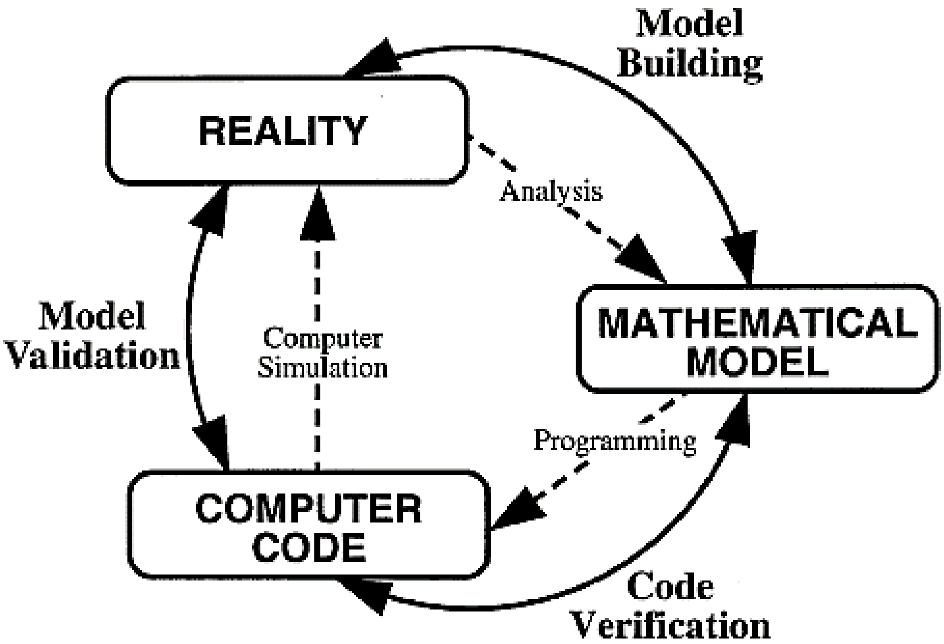

Figure-5.1. Relationship of numerical modelling with experimental study (Oberkampf 2001)

In this study, the experimental results of petroleum diesel fuel (PDF) were compared with the numerical simulation and modelling data obtained by using waste plastic fuel (WPF). Simulation study was based on a four-stroke diesel engine similar to the Yanmar L48N. The complete specifications of the numerical model are given in the Appendix-C. A comparison of engine performance and emission characteristics is given as follows,

5.2. Engine Torque

The values of engine torque for the average of three experimental and simulation runs are shown in the Figure-5.2. For both types of fuels, engine torque increased proportionally with the escalation of rpms. For the case of PDF, this change was much uniform and ranged from 9.2 Nm to 11.2 Nm. Whereas, for WPF, this variation was more pronounced ranging from 3.25 Nm to 12.5 Nm. At the lowest rpms, simulation torque was ~60% less than the experimental torque. However, this behaviour considerably changed at 2600 rpms and simulation torque was 11% higher.

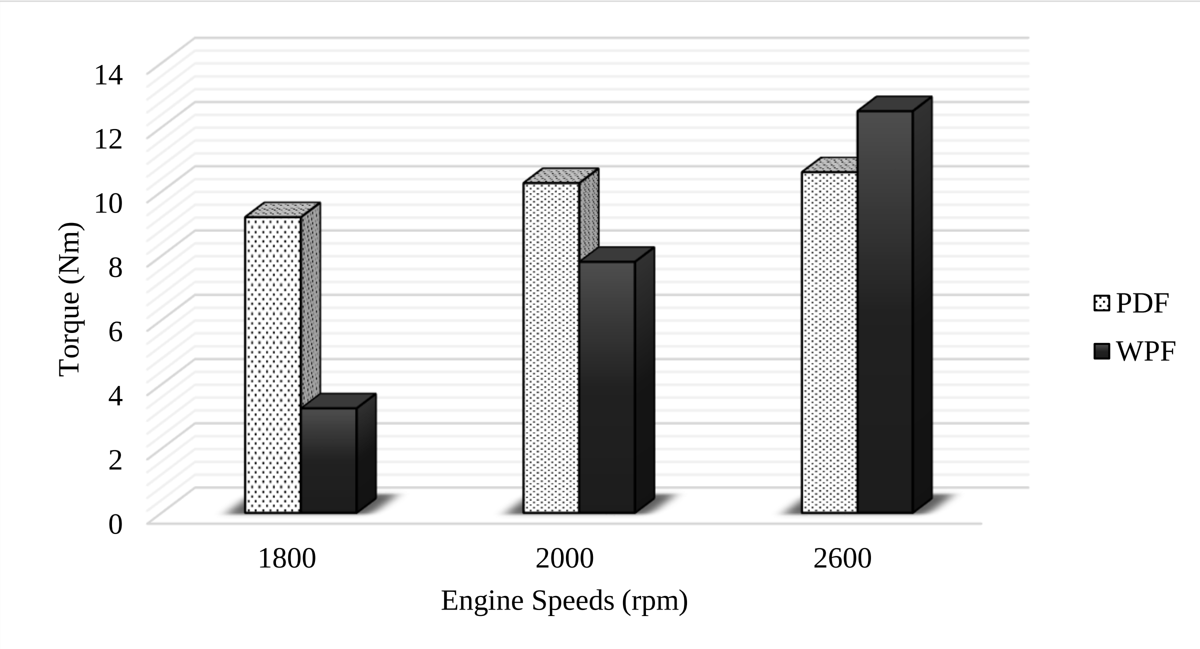

Figure-5.2. Comparison of experimental and simulation results of torque

As before, the highest torque was obtained at 2600 rpm for both experimental and simulation runs. This behaviour is similar to the engine's standard performance curves given in the previous section. Moreover, a previous study (Poompipatpong et al. 2014) comparing PDF and waste plastic oil has also reported similar observations as shown in the Figure-5.3. They used PDF and WPO blends in different percentages ranging from 25% to 75% in a 6-cylinder, 4-stroke direct injection diesel engine and observed an increase in the engine torque up to certain rpms.

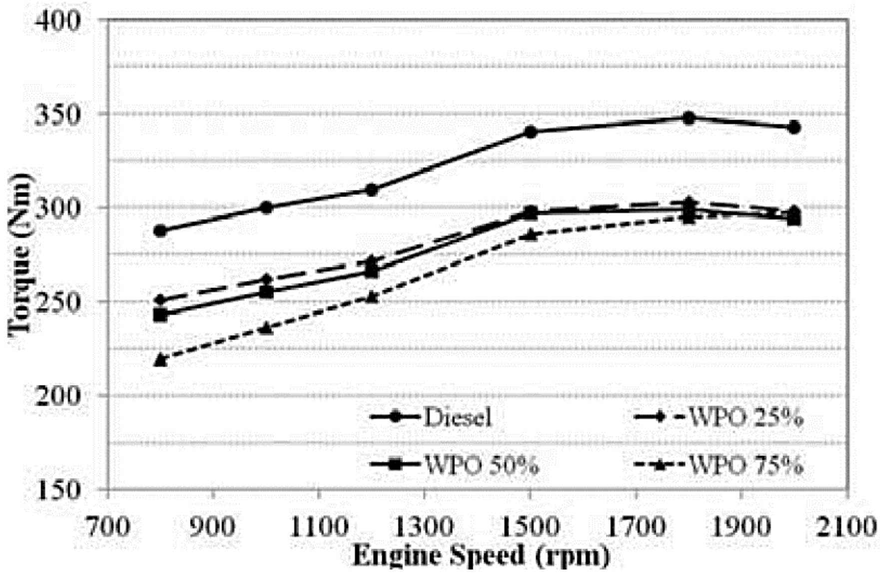

Figure-5.3. Variation of torque with engine speed for pure PDF and PDF-WPF blends, adapted from Poompipatpong et al. (2014)

5.3. Engine Power

Similar to the engine torque, there was an exponential increase in engine power output with higher revolutions, as shown in the Figure-5.4.

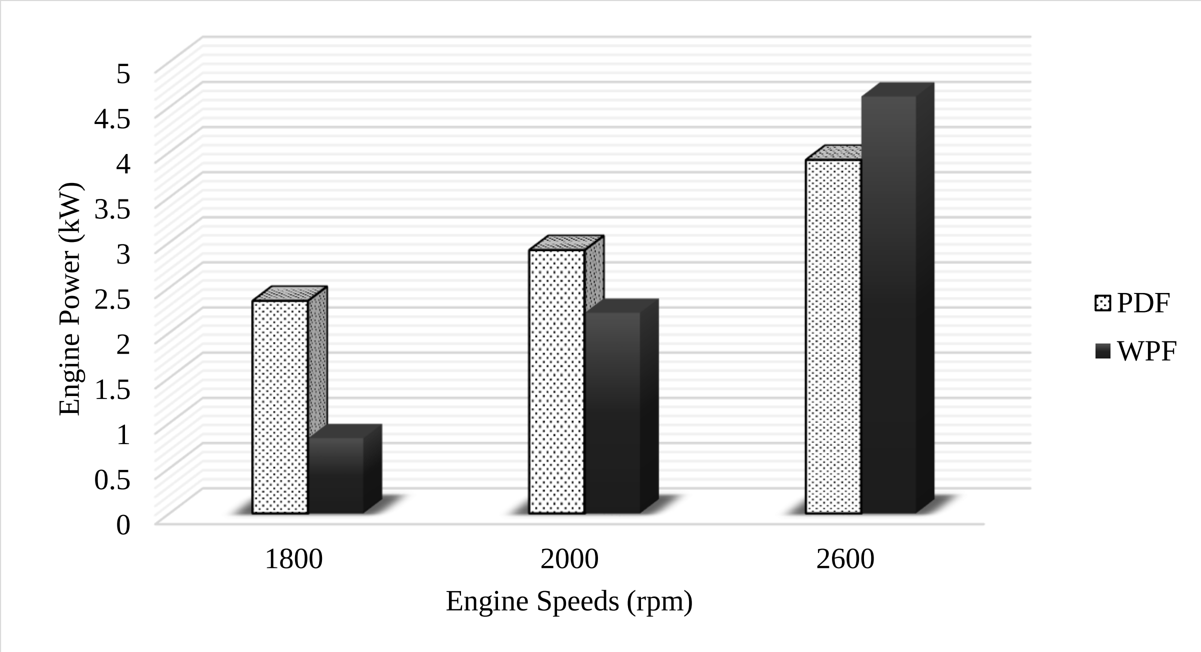

Figure-5.4. Comparison of experimental and simulation results of engine power

This trend existed for both types of fuels for the whole spectrum of rpms. For PDF, the average power varied from ~2 kW at 1800 rpm to 11.28 kW at 2600 rpms. In case of simulation results, the power output ranged from 0.83 to 4.6 kW at the lowest and highest rpms respectively. As before, the average experimental power output at maximum rpms was 11% less than the simulation power. Similar findings have been reported by Poompipatpong et al. (2014) (Figure-5.5) and Rinaldini et al. (2016) in their studies on conventional diesel and WPO. They also experienced an exponential increase in power for the whole rpm range for all fuel types.

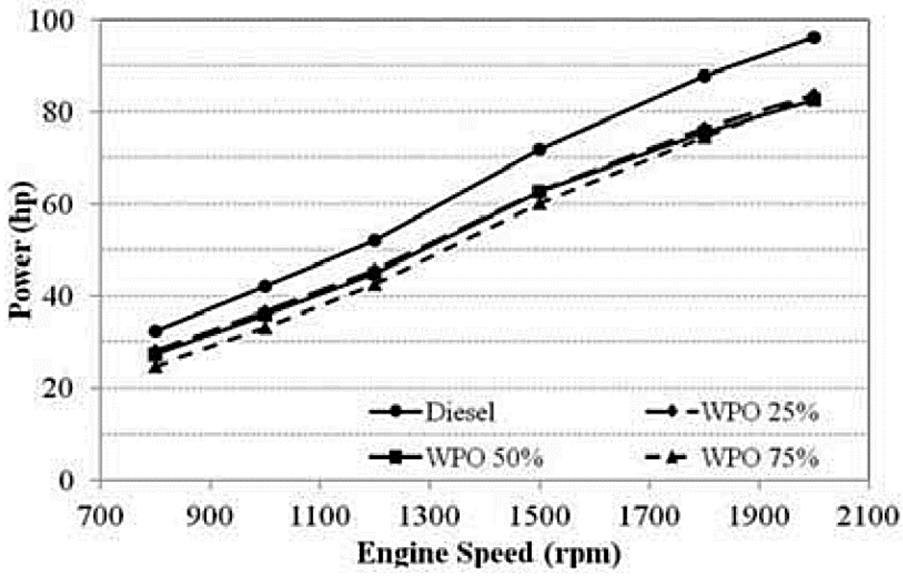

Figure-5.5. Variation of engine power with speed for pure PDF and PDF-WPF blends, adapted from Poompipatpong et al. (2014)

5.4. Exhaust Temperature

Figure-5.6 displays the comparative results of exhaust temperatures at various engine speeds. It is evident that both experimental and simulation exhaust temperatures increased from 1800 rpm to 2600 rpm. However, on average, the simulation temperature was 8% higher than the experimental temperature at all speeds. In case of WPF, the concentration of oxygen is much higher which leads to higher ratio of air-fuel and causes complete combustion. Such combustion, along with a longer ignition delay, leads to higher combustion chamber and exhaust temperatures (Mani et al. 2011; Kumar et al. 2012).

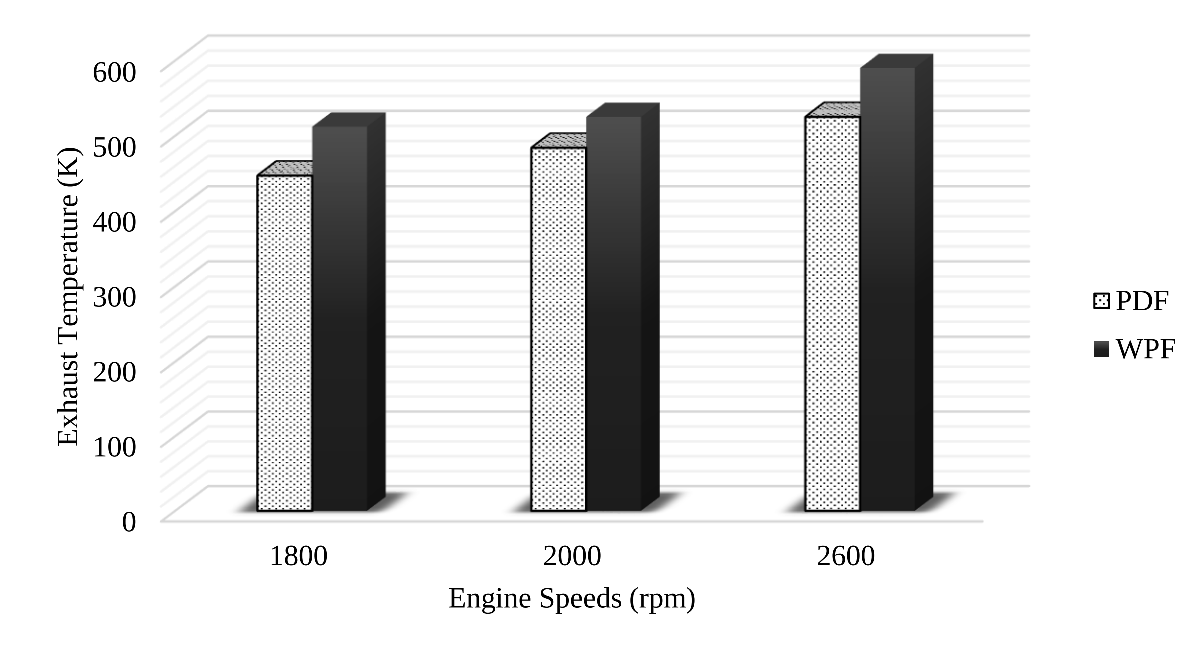

Figure-5.6. Comparison of experimental and simulation results of exhaust temperatures

It is expected, that similar circumstances might have contributed to the high simulation exhaust temperatures in this study. In another research, Cleetus et al. (2013) also reported a high exhaust temperature based on the results obtained by using different blends of WPF with PDF. As shown in the Figure-5.7, PDF blend having 20% WPF (B20) exhibited higher exhaust temperature for all observations as compared to the pure PDF. It was found that the same reasons, as mentioned previously, were responsible for high exhaust temperature. The B20 caused an ignition delay of 2.5^{o} crank angle that intensified the engine peak pressure leading to high temperature of the exhaust.

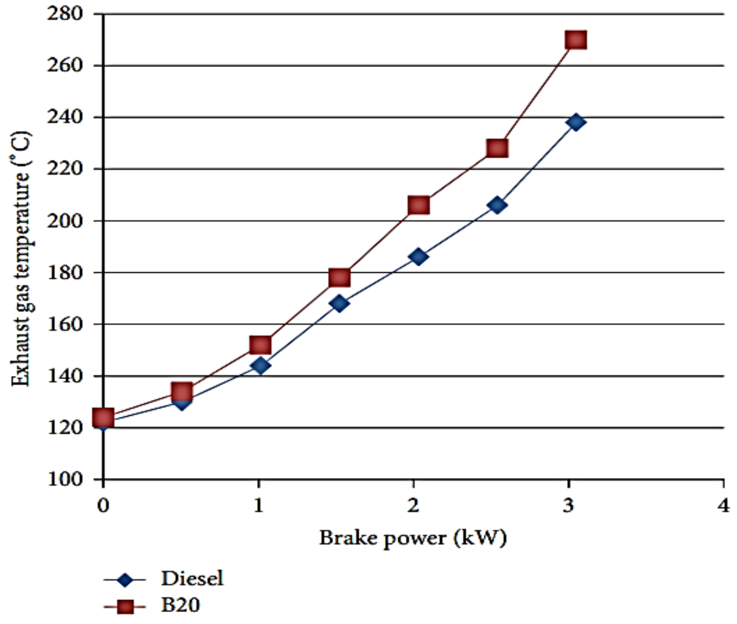

Figure-5.7. Comparison of exhaust temperatures of two fuels, adapted from Cleetus et al. (2013)

5.5. NOx Emissions

Figure-5.8 displays a comparison of experimental vs. simulation NOx emissions at the three engine speeds. As expected, the simulation NOx remained higher than the experimental NOx for all runs. At 1800rpm, the simulation NOx emission was maximum having a value of 780ppm. At higher engine speeds, it decreased gradually and followed a trend similar to experimental emissions. It should be noted here that the NOx emissions are highly dependent on the temperature of combustion chamber and the available oxygen.

The WPF possesses higher concentration of oxygen as compared to the PDF. As a result, the local air-fuel ratio is much higher and causes complete combustion takes place. However, such combustion leads to higher combustion chamber temperature which, along with surplus amount of oxygen, leads to the formation of abundant thermal NOx (Agarwal & Das 2001). According to Tesfa et al. (2014) and Rinaldini et al. (2016), the presence of higher aromatic content in WPF is also responsible for higher NOx emissions. Aromatic compounds have higher adiabatic flame temperature as compared to components present in PDF. This leads to higher rate of heat formation, which increases combustion chamber temperature.

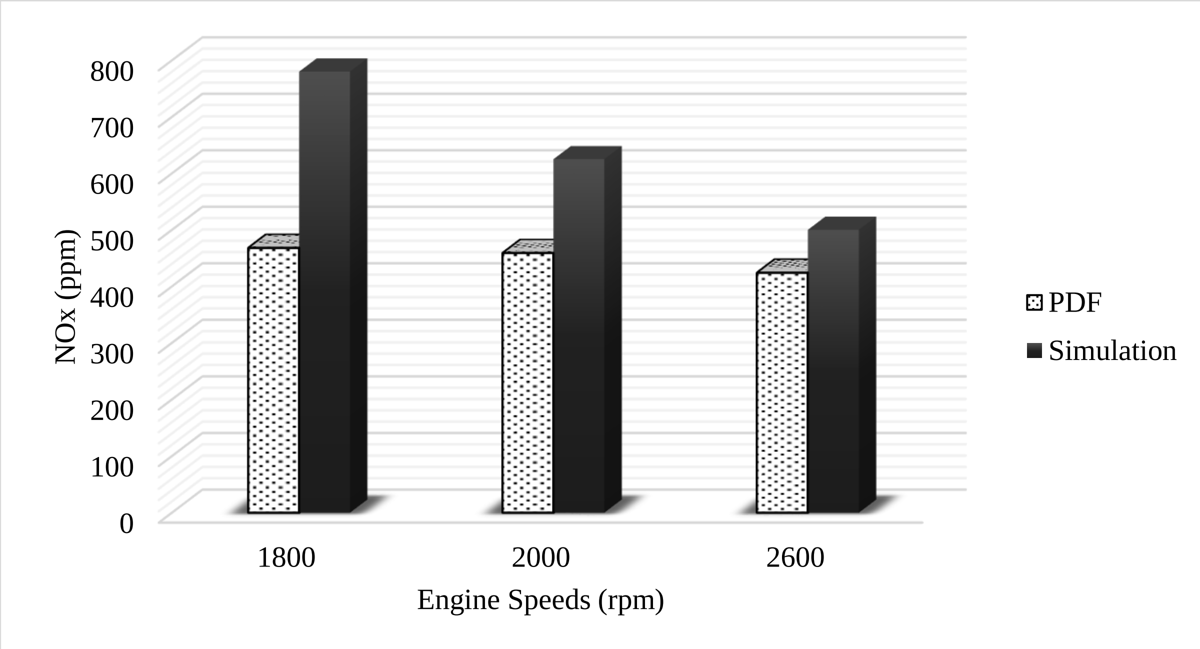

Figure-5.8. Comparison of experimental and simulation results of NOx emissions

5.6. Summary

In this chapter, the purpose of modelling and simulation studies as elaborated and the results were compared with the real-life experimental observations. The specifications given in the Appendix-C formed the basis of a numerical model based on a four-stroke diesel engine similar to Yanmar L48N. In case of engine performance, on average, the simulation torque and power were ~40% less than the experimental values at the first two rpms. However, at 2600 rpm, the simulation values were nearly 11% higher than the experimental values for both parameters. Similar behaviour was observed in the simulation exhaust temperature that remained 8% higher (on average) than the experimental temperature at all speeds. The simulation NOx emissions remained higher for all engine speeds ranging from 780 ppm to 500 ppm. The probable reasons behind these trends have been discussed in detail in this section, also keeping in view the previous research studies. The key conclusions drawn from this study are elaborated in next section and the suitable recommendations for future research work are discussed in detail.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The present study investigated the performance and emissions characteristics of a four-stroke diesel engine (Yanmar L48N) by using two types of fuels, i.e. PDF and WPF. Experimental studies conducted by using PDF produced well-defined performance and emission data for engine speeds ranging from 1800 rpm to 3800 rpm. In a similar manner, the simulation data relating to performance characteristics and NOx emissions was obtained at three engine speeds (1800, 2000, and 2600 rpm). This data was obtained by simulating a test engine, having characteristics similar to the Yanmar L48N, in ANSYS 19.2 software.

A comparison of experimental and simulation results revealed that the average experimental torque was 59% higher than the simulation torque at 1800 rpm. As the engine speed increased, this different decreased to 20% and, at the maximum rpm this behaviour was reversed. The simulation torque was 11% higher than the experimental value. Similar trends were obtained for the experimental and simulation power output.

The simulation exhaust temperature, on average, remained 8% higher than the experimental temperature for all engine speeds. Similarly, the NOx emissions were also higher as compared to the experimental runs. The simulation performance data were very much similar to the expected trends, but there were also some unexpected variations not experienced previous researchers. The probable reasons behind these trends have been discussed in detail in the previous section.

6.2. Recommendations

Based on the results obtained in this study, a number of recommendations useful for future research in can be made which are discussed as follows.

- In this study, the simulation results were limited to three engine speeds for comparing the performance and emission characteristics. A more elaborate study can be dedicated to simulation studies covering a broad spectrum of engine speeds and performance or emission characteristics.
- In the simulation, only a 45° sector of the combustion chamber was studied. This enabled us to obtain the required simulation data with limited computational load and time. In future, this study can also be extended to more sectors of combustion chamber, such as 90° sectors.
- As mentioned previously, n-decane was used as surrogate for WPF for conducting the simulation runs. However, a more elaborate variety of carbon compounds could be added to the composition of WPF surrogate used in ANSYS Fluent.
- Considering the experimental/numerical results obtained in this study and the findings reported by previous similar studies, it is expected that blends of PDF-WPF could give better engine performance/emissions results. This will also enable us to understand the underlying mechanisms responsible for the difference in results.

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APPENDIX-A (Project Specifications)

ENG4111/4112 Research Project

Project Specification

For:	Abdullah Murad
Title:	The Experimental & Simulation Investigation of the Engine Performance Characteristics of Conventional and Waste Plastic Fuel
Major:	Mechanical Engineering
Supervisor:	Dr. Saddam H. Al-lwayzy
Sponsorship:	Kuwait Culture Office
Enrolment:	[redacted]
Project Aim:	To study the production, properties and engine performance characteristics of biodiesel produced from mixed waste plastic
Programme:	**Version 1, 20th March 2019**

1. To develop a basic understanding on environment friendly fuels by reviewing previous researches working on biodiesel production from various resources
2. To narrow down the focus to fuel/oil produced from plastic waste, understand the production mechanisms and its characterisation methods
3. To investigate the engine performance characteristics of waste plastic fuel and conventional diesel mixtures in various proportions
4. To construct a performance map of engine's output and finding out the limitations posed by waste plastic fuel in modern diesel engines

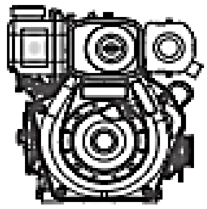
   If time and resources permit:

5. Collection and analysis of exhaust gases obtained by using various fuel mixtures in a diesel engine

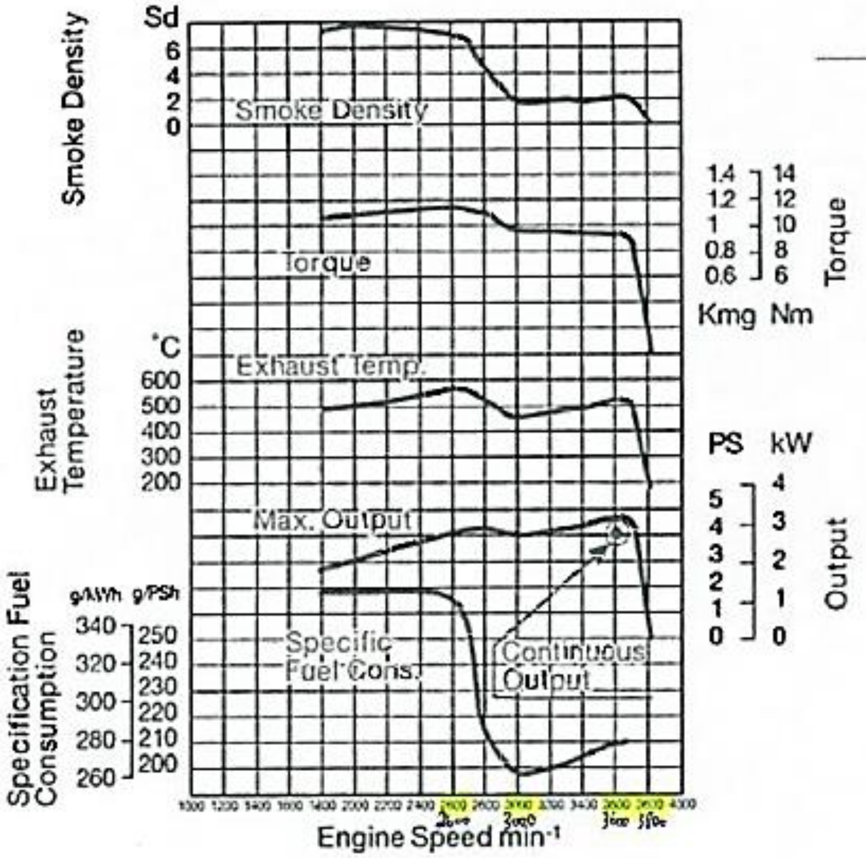
Risk Management Plan

A detailed risk management plan will be developed which will include probable risks, their consequences, and recommended course of actions. This plan will be included in tabulation form in the project report.

APPENDIX-B (Engine Specifications & Performance Curves)

Engine Series				
Engine Model			L48N	
				
Type				
No. of Cylinders				
Bore x Stroke		mm	Φ70 x 57	
Displacement		liter	0.219	
Continuous Rated Output	Engine Speed	rpm(min⁻¹)	3600	3000
	Output	kW[hp]	3.1[4.2]	2.8[3.8]
Maximum Rated Output	Engine Speed	rpm(min⁻¹)	3600	3000
	Output / Eng. Speed	kW[hp]	3.5[4.7]	3.1[4.2]
High Idling		rpm(min⁻¹)	3800±30	3175±30
Engine Weight (Dry)	Electric Starter	kg	32.0	
	Recoil Start	kg	27.0	
Cooling System				
Lubricating System				
Starting System				
Dimension	Overall Length (L)	mm	332	
	Overall Width (W)	mm	384	
	Overall Height (H)	mm	417	
Lubricating System	Dispstick Upper Limit	liter	0.8	
	Dispstick Lower Limit	liter	0.6	
Fuel Oil Tank Capacity		liter	2.4	

L48N6



Notes: This performance is under the following condition.
After 30 hrs. initial running
Atmospheric conditions: Temperature 298 K (25°C)
Pressure 100 kPa (750 mmHg)
Humidity 30%

APPENDIX-C (Numerical Model Parameters & Calculations)

A number of parameters were selected for the numerical analysis such as solving method, boundary conditions, analysis modals and solution methods. These are given in the following table,

ICE Parameters	
Connecting Rod Length	114 mm
Minimum Lift	0.2 mm
Cone Angle	15^{o}
Inlet Valve Closed	570
Exhaust Valve Open	833
No. of Crank Angles	263
Engine Cycle	Combustion Stroke Only
Cycle Type	Four Stroke
Geometry Parameters	
Decomposition Position	IVC

Sector Angle	45^o
Compression ratio	20:1
Spray Location Height	0.03 mm
Spray Location Angle	0.05 mm
ICE Solver Parameters	
Engine Speeds	1800 rpm, 2000 rpm, 2600 rpm
Engine Type	CI Engine
Species Model	Diesel Unsteady Flamelet
Fuel	$C_{10}H_{22}$ (n-decane)
Auto Save Type	Crank Angle
Pollutant	NOx, Soot
Parameters of Boundaries	
ICE-Sector Top Faces	Boundary Condition Type: wall Temperature: 602K
ICE-Piston	Boundary Condition Type: wall Temperature: 645K

ICE-Cyl-Piston	Boundary Condition Type: wall Temperature: 567K
Fluent Setup Parameters	
Solving Method	Pressure-based Solver
Energy Equation	On
Viscous Model	k-epsilon
NOx Model	On
Soot Model	On
Discrete Phase	On
Solution Initialization	Standard
Precision	Double
Solution Method for Energy	Second Order Upwind

APPENDIX-D (Risk Assessment)

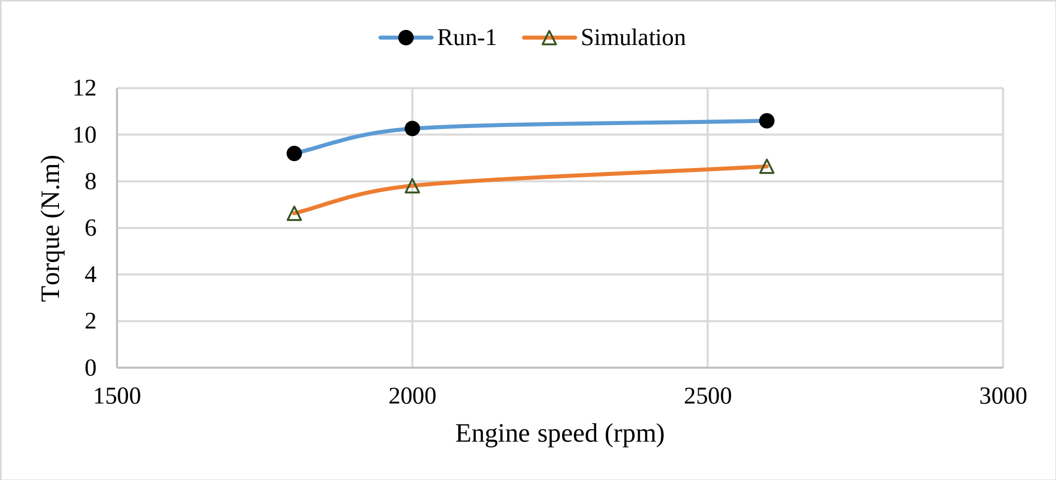
A risk management plan relating to the present experimental setup is shown in the table. It covers all possibilities of engine performance issues.

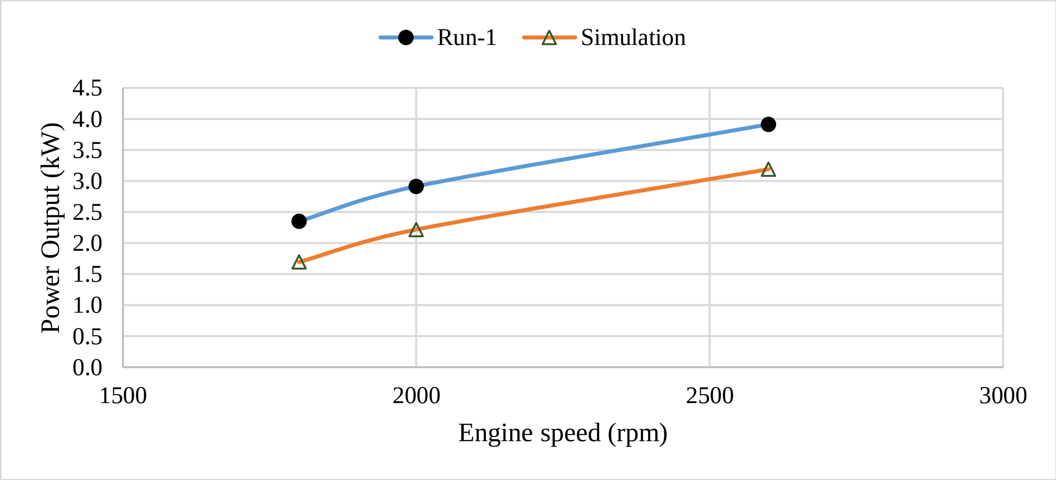
Table 3.Risk Management Plan

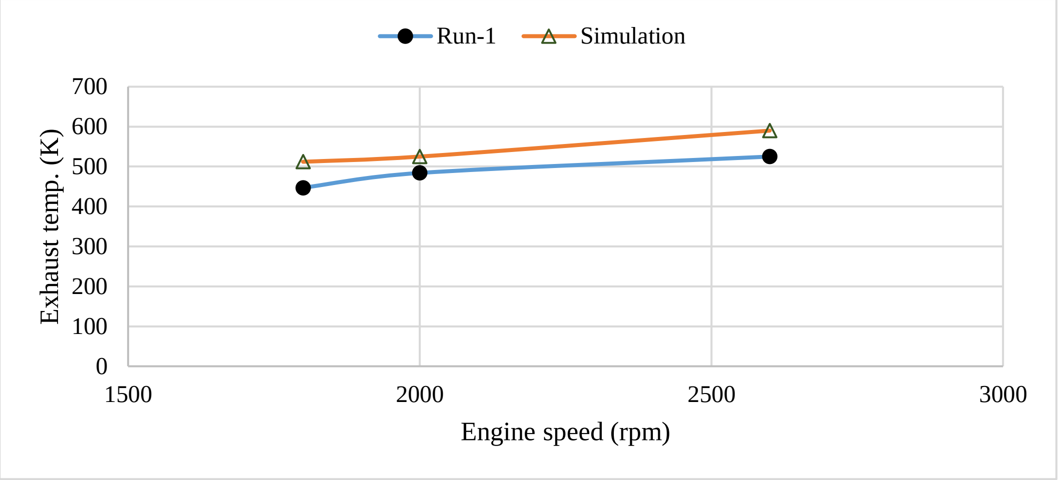
Sr. No.	**risk item**	**Possible effect**	**Recommended action**
1.	Engine cooling insufficient or complete failure	Engine overheating or damage to the surrounding	The cooling system must be analysed thoroughly for obtaining maximum efficiency of the engine
2.	Engine dynamometer unreliable or completely failed	The control system will not be able to characterise the engine torque	The dynamometer must be characterised and an accurate control system must be effectively used
3.	Too lean Air/ fuel ratio	The normal operation of engine will be damaged and harmful gases will be emitted	The air to fuel ratio should be carefully controlled before testing any other control system
4.	The control system is unable to accurately predict fuel consumption and power output	The normal working of the engine will be damaged	A calibration of the fuel flow systems should be performed and optimisd accordingly

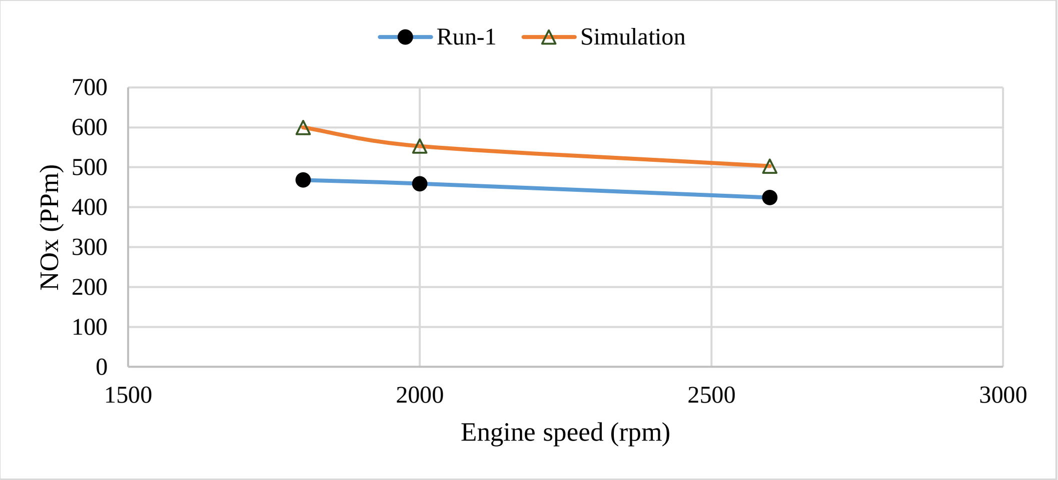
APPENDIX-E (Comparison of Individual PDF Runs with Simulation)

Run-1

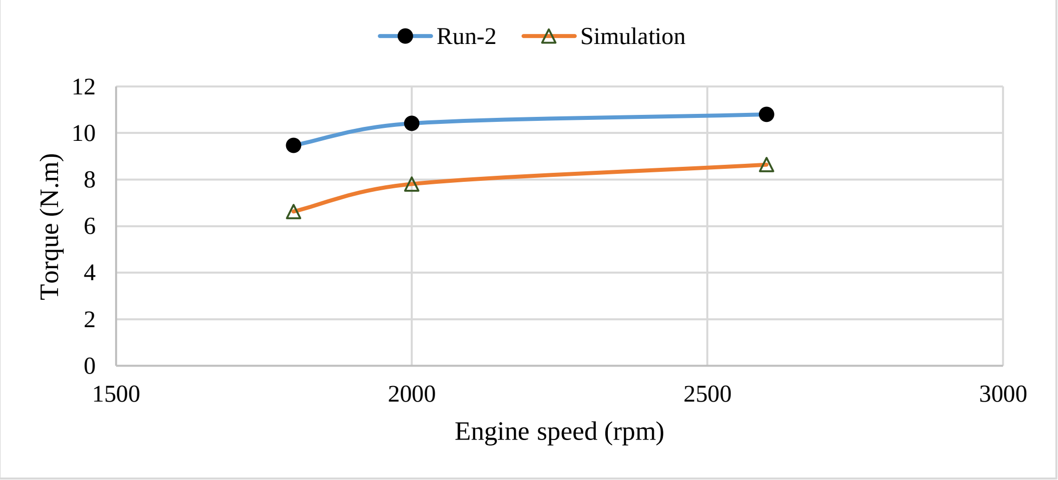


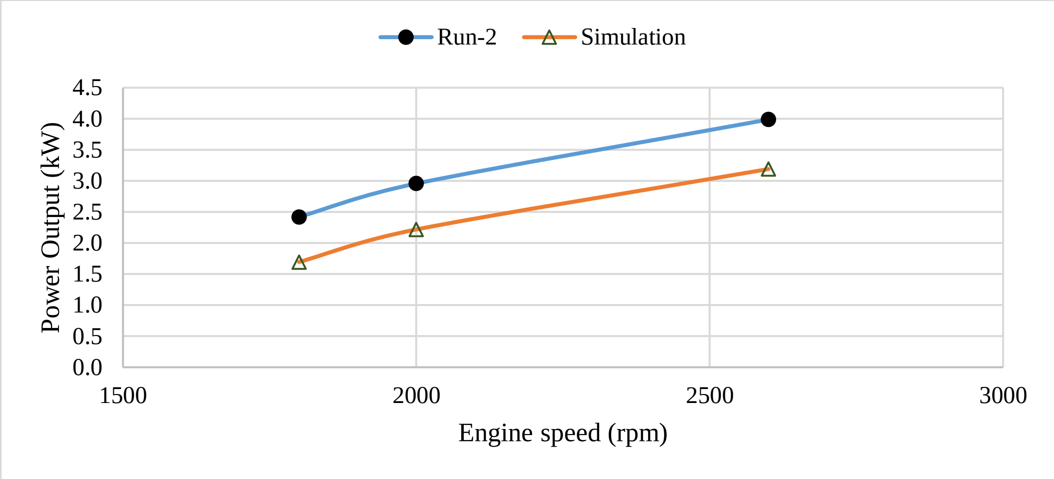


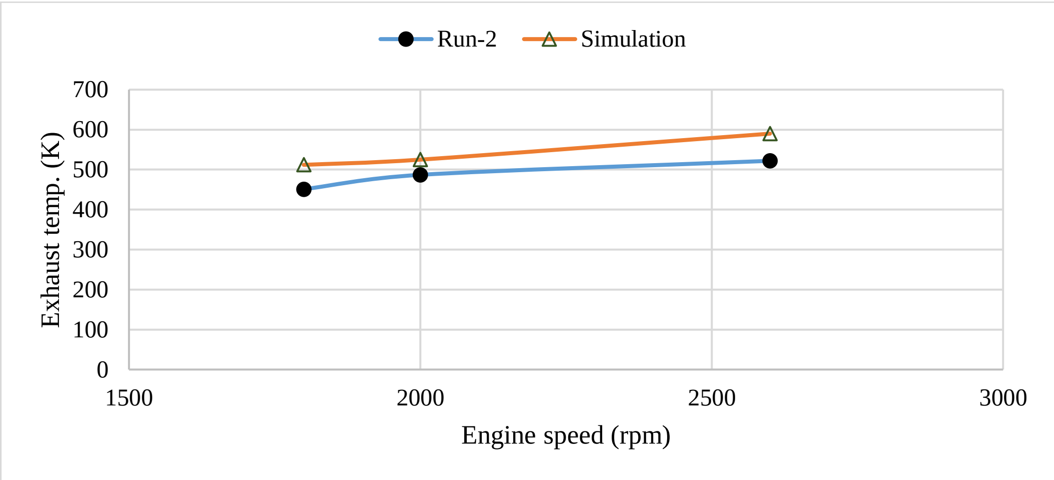

Run-1
Simulation
700
600
500
400
300
200
100
0
Exhaust temp. (K)
1500
2000
2500
3000
Engine speed (rpm)

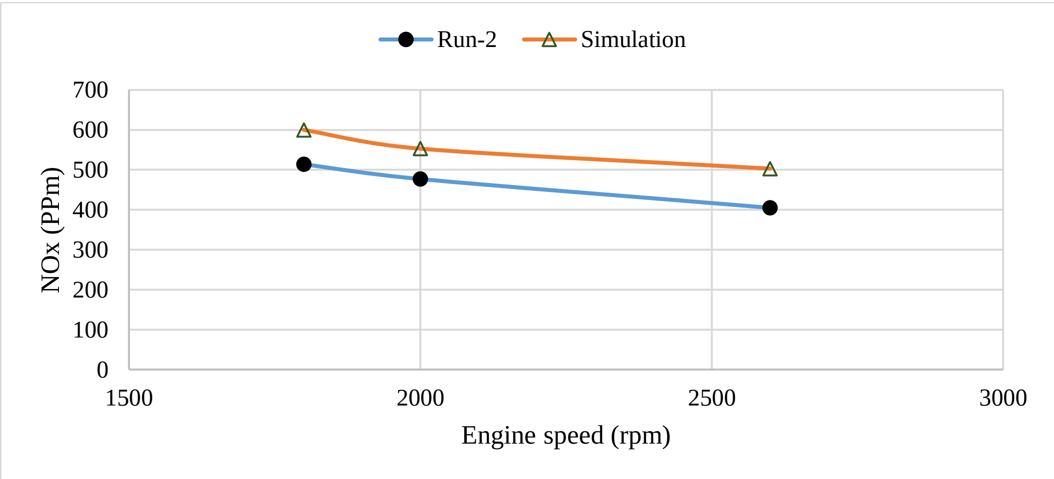

Run-1
Simulation
700
600
500
400
300
200
100
0
NOx (PPm)
1500
2000
2500
3000
Engine speed (rpm)

Run-2

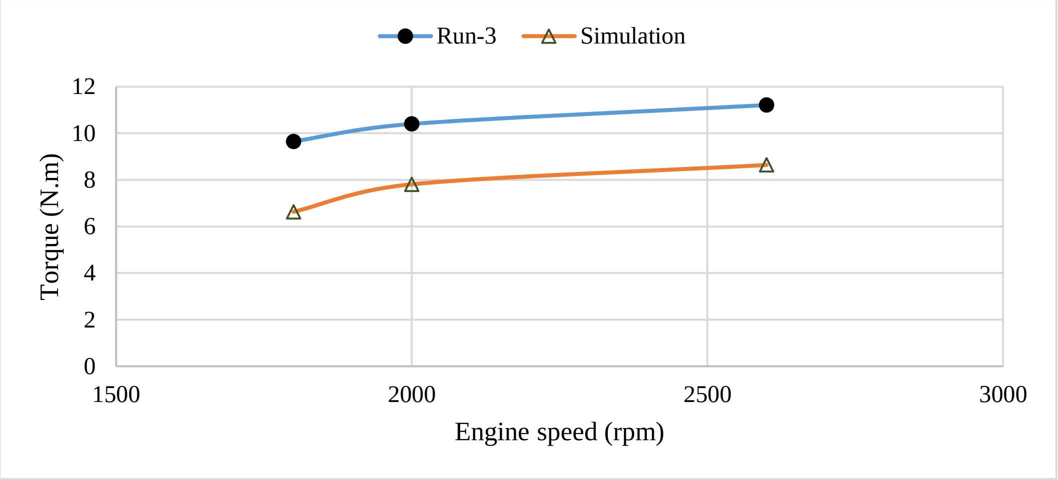

Run-2
Simulation
12
10
8
6
4
2
0
Torque (N.m)
1500
2000
2500
3000
Engine speed (rpm)

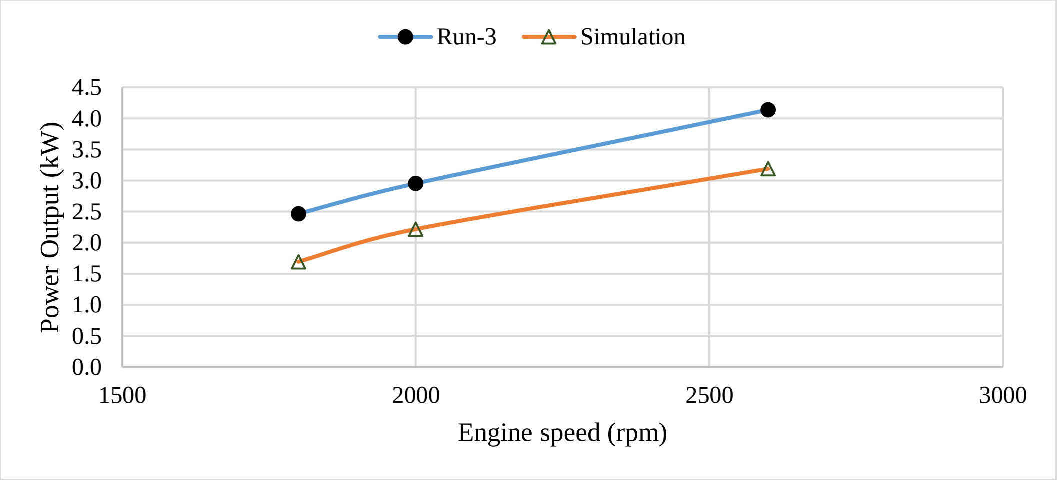

Run-2
Simulation
Power Output (kW)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1500
2000
2500
3000
Engine speed (rpm)

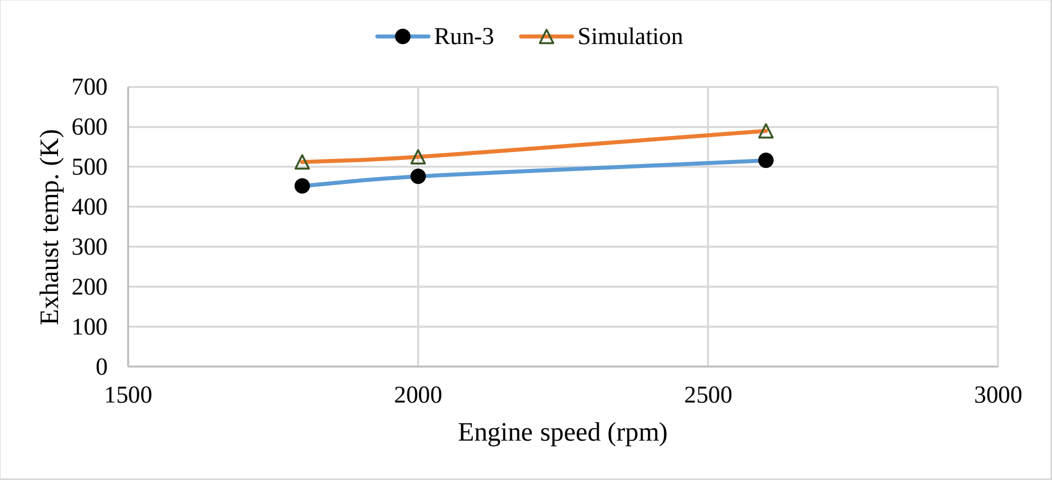

Run-2
Simulation
Exhaust temp. (K)
700
600
500
400
300
200
100
0
1500
2000
2500
3000
Engine speed (rpm)

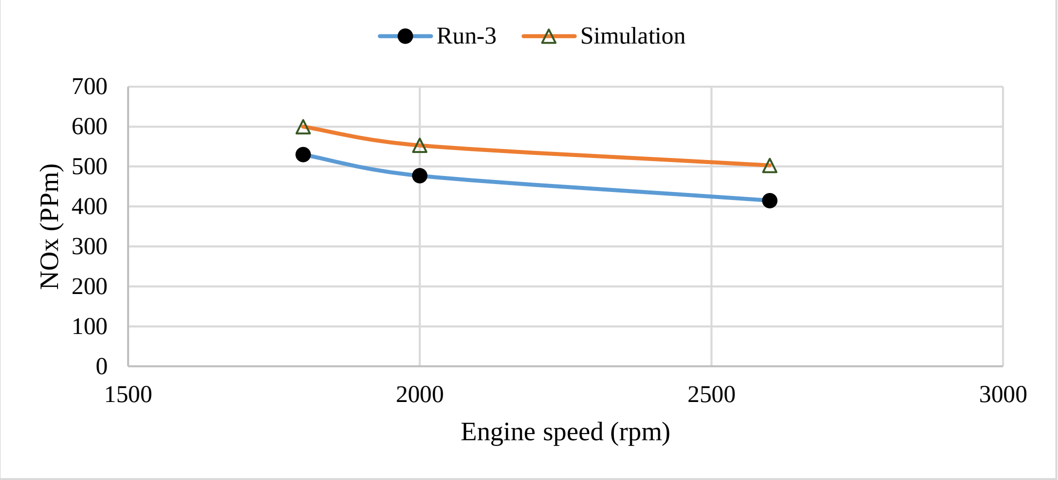

Run-2
Simulation
NOx (PPm)
700
600
500
400
300
200
100
0
1500
2000
2500
3000
Engine speed (rpm)

Run-3


Run-3
Simulation
12
10
8
6
4
2
0
Torque (N.m)
1500
2000
2500
3000
Engine speed (rpm)


Run-3
Simulation
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Power Output (kW)
1500
2000
2500
3000
Engine speed (rpm)


Run-3
Simulation
700
600
500
400
300
200
100
0
Exhaust temp. (K)
1500
2000
2500
3000
Engine speed (rpm)



Run-3
Simulation
700
600
500
400
300
200
100
0
NOx (PPm)
1500
2000
2500
3000
Engine speed (rpm)