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Review

Waste oils as alternative fuel for diesel engine: A review

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Increase in energy demand, stringent emission norms and depletion of oil resources have led the researchers to find alternative fuels for internal combustion engines. On the other hand, waste oils pose a very serious environment challenge because of their disposal problems all over the world. In this context, waste oils are currently receiving renewed interest. The properties of the oil derived from waste plastics, cooking and engines oils were analyzed and compared with the petroleum products and found that it has properties similar to that of diesel. This paper gives a brief review about using waste oil of these three types of oil as a fuel for diesel engines. The conversion process of each type of waste oil is presented. The results obtained from the experimental studies on a diesel engine are discussed.

Key words: Waste oil, cooking, plastic, conversion, fuel, engine.

INTRODUCTION

The threat posed by climate change and the striving for security of energy supply is issues high on the political agenda these days. Governments are putting strategic plans in motion to decrease primary energy use, take carbon out of fuels and facilitate modal shifts (Sebastian and Thomas, 2009). Throughout the world, many steps are being taken to alternate petroleum based fuel due to tires from automotive vehicles, restaurant and plastic have become increasingly hard. Waste management is the impact of increase in oil price and the reality of petroleum depletion. Additionally, the disposals of waste once a technical problem that has to be solved under thrifty, yet environmentally acceptable and hygienic conditions and preferably performed by skilled labor. Disposal of waste vehicle tires is one of the most important problems that should be solved. It is estimated that worldwide, over one billion waste tires are generated annually (Cumali and Hüseyin, 2011). Industrial and household wastes are produced on a daily basis and are managed in many ways, depending on their type. According to their combustibility, wastes are basically categorized as either burnable or unburnable. The burnable wastes are normally treated by combustion with or without heat production, while the unburnable wastes are treated by recycling, re-use, or landfilling, depending on the material. Municipal and industrial wastes that contain high heat value, such as waste plastics oil (WPO), waste cooking oil (WCO), and waste lubricating oil (WLO) are considered efficient feedstocks for energy production in a Waste-to-Energy regimen (Ampaitepin and Tetsuo, 2010). The main objective of this paper is to analyze by means of literature review the engine performance, combustion and emission characteristics of diesel engines fuelled with biodiesel produced from waste engine, waste cooking and waste plastic oil and/or its blends with petroleum-based diesel fuel.

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Abbreviation: ATDC, Before top died centre; **Bsfc,** break specific fuel consumption; **Bmep,** break mean effective pressure; **CA,** Crank angle; **DF,** diesel fuel; **DLF,** diesel-like fuel; **FFA,** free fatty acid; **GLF,** gasoline-like fuel; **PM,** particulate matter; **Rpm,** revolution per minute; **SI,** spark ignition; **THC,** total hydrocarbons; **UCO,** used cooking oil; **WPO,** waste plastic oil; **WCO,** waste cooking oil; **WEO,** waste engine oil; **WEO100,** pure (100%) waste engine oil; **WEO75,** mixture of 75% WEO and 25% diesel fuel; **WEO50,** mixture of 50% WEO and 50% diesel fuel.

WASTE OIL AS FUEL FOR DIESEL ENGINES

Waste engine oil

Waste lubricant oils and biofuels are two important alternative fuel sources proved to be the best substitutes for existing petrofuels, since waste generated oils represent more than 60% of used lubricant oils. Therefore, waste oils are one of the most abundant pollutant residues that are generated nowadays, reaching the value of 24 million metric tonnes per year (Fuentes et al., 2007). In recent years, recycling of the waste lubricant oils and utilizing of the products as fuels have become important topics for researchers. Most of the lubricant oils are generally obtained from petroleum resources. Petroleum-derived base oils currently account for about 97% of the total lubricant production (Bhaskar et al., 2004). However, these oils become waste oils harmful for environment after a certain time period. Recycling of the waste lubricant oils by purifying and converting them into fuels is very important in terms of protection of the environment. After waste lubricant oils are converted into fuels, they can be used as fuels in internal combustion engines. In recycling process, waste lubricant oils are exposed to various processes, and then used as fuel or they are converted into various chemicals in order to minimize the harmful effects of these wastes (Bhaskar et al., 2004).

Millions of tons of used oils are disposed through dumping on the ground or in water, land filling, or non-energy-recovery (Bhaskar et al., 2004). The used or waste oils can be refined and treated to produce fuels or lubricating oil base stock. On the other hand, the waste oils pose an environmental hazard due to both their metal content and other contaminants (Nerin et al., 2000). The high-volume waste oils can be turned into valuable fuel products by refining and treating processes. Converting of the waste oils into diesel and gasoline-like fuels to be used in engines without disposing is very important. Utilization of the diesel and gasoline-like fuels produced from the waste lubricant oils, and blending of the produced fuels with gasoline or turpentine decrease consumption of petroleum based fuels, protecting environment from toxic and hazardous chemicals (Bhaskar et al., 2004). It also saves of foreign exchange, reduces greenhouse gas emissions and enhances regional development especially in developing countries (Demirbas and Demirbas, 2007).

Characteristics of any fuel are very important from the point of deciding whether the fuel can be used for desired application or not. Therefore, some characteristics of the produced diesel-like fuel and gasoline-like fuel are shown in Tables 1 and 2, respectively, together with standard values of a diesel and gasoline fuel. The table shows that some of the parameters of density, boiling point, viscosity, flash point and lower heating value are in the standard values of the diesel oil or reasonably close to the standard values. But, sulfur amount is considerably higher than that value. It should be decreased below the value of 50 ppm.

Waste cooking oil

Many researchers have tried to develop vegetable oil-based derivatives that approximate the properties and performance of petroleum-based diesel fuel. Esters of fatty acids (biodiesel), derived from the transesterification of vegetable oils have properties similar to petroleum-based diesel fuel (Enweremadu and Rutto, 2010). Literature is replete with advantages derived using biodiesel: it helps to reduce the carbon dioxide emission to the atmosphere, it is renewable in nature and safer to handle, it has no aromatic compounds, practically no sulphur content, and oxygen atoms in the molecule of fuel may reduce the emissions of carbon monoxide (CO), total hydrocarbon (THC) and particulate matter (PM) (Lapuerta et al., 2002; Alamu et al., 2008). However, biodiesel is known to have some drawbacks when compared with petroleum-based diesel fuel such as worse low temperature properties, greater emissions of some oxygenated hydrocarbons, higher specific fuel consumption, decrease in brake thermal efficiency and higher production cost (Dunn et al., 1996; Canakci and Van-Gerpen 2001). The problem of production cost has been partially solved by the use of waste cooking or animal fats as the raw materials in the transesterification process (Dorado et al., 2003, 2004).

However, during frying, vegetable oil undergoes various physical and chemical changes, and many undesirable compounds are formed. These include free fatty acid and some polymerized triglycerides which increase the molecular mass and reduce the volatility of the oil. Therefore, fatty acid esters obtained from frying oil influences the fuel characteristics (such as the viscosity and it is believed that the burning characteristics reduce) leading to a greater amount of Conradson carbon residue (Kulkarni and Dalai, 2006). Comprehensive reviews on biodiesel production from used cooking oil (UCO) can be found in (Kulkarni and Dalai, 2006; Enweremadu and Mbarawa, 2009). Table 3 shows a comparison of fuel properties for a WCO biodiesel and diesel fuel.

Currently, compared to petroleum-based diesel, the high cost of biodiesel is a major barrier to its commercialization. It is reported that approximately 70-85% of the total biodiesel production cost arises from the cost of raw material. Use of low-cost feedstock such as WCO should help make biodiesel competitive in price with petroleum diesel. Numerous studies have been conducted on biodiesel production and emission testing in the past two decades. Most of the current challenges are targeted to reduce its production cost, as the cost of biodiesel is still higher than its petro-diesel counterpart. This opens a golden opportunity for the use of WCO as

Table 1. Comparison of diesel-like fuel obtained from waste lubrication oil and diesel fuel (Arpa et al., 2010a).

Properties	Diesel fuel	DLF
Density at 15℃ (kg/m^3)	820-845	818
Viscosity at 40℃ (mm^2/s)	2-4.5	3.49
Flash point (℃)	>55	57
Sulfur (ppm)	50	3500
Water (mg/kg)	<200	130
Lower heating value (kJ/kg)	42.700	42.500
Temperature at 250℃, max. volume (%v/v)	65	20
Temperature at 250℃, min. volume (%v/v)	85	90
Volume at 95%, max. temperature (℃)	360	360

Table 2. Comparison of gasoline-like fuel obtained from waste lubrication oil and diesel fuel (Arpa et al., 2010b).

Properties	GLF	Unleaded gasoline
Density at 15℃ (kg/m^3)	740	780
Flash point (℃)	25	-43
Lower heating value (kJ/kg)	43.000	43.890
Distillation range (℃)		
IBP (initial boiling points)	38	34
10 vol.%	68	53
50 vol.%	126	92
90 vol.%	223	154
End point	262	218

Table 3. Comparison of fuel properties for a WCO and diesel fuel (Enweremadu et al., 2010).

Characteristics	Waste cooking oil	Diesel
Density at 40℃ (kg/m^3)	876.08	807.3
Specific gravity at 15.5℃	0.893	0.825
Distillation temperature		
10% recovery temperature	340	165
50% recovery temperature	345	265
90% recovery temperature	320	346
Flash point (℃)	160	53
Fire point (℃)	164	58
Kinematic Viscosity at 40℃ (mm^2/s)	3.658	1.81
Calorific value (kJ/kg)	39767.23	42347.94
A.P.I gravity	26.87	39.51
Cetane index	50.54	46.21
Aniline point (℃)	NA	77.5

its production feedstock. Everywhere in the world, there is an enormous amount of waste lipids generated from restaurants, food processing industries and fast food shops everyday (Xiangmei et al., 2008). In China, with annual consumption of edible oils approaching 22 million tons, the country generates more than 4.5 million tons of used oil and grease each year, roughly half of which could be collected through the establishment of an integrated collection and recycling system. Those 2 million tons of “ditch oil” alone would guarantee the smooth operation of all current biodiesel production lines. Reusing of these waste greases cannot only reduce the

Table 4. Comparison of fuel properties from waste plastic oil and diesel fuel (Mani et al., 2009).

Property	Waste plastic oil	Diesel
Density at 30℃ in gm/cc	0.8355	0.840
Ash content, %	0.00023	0.045
Gross calorific value (kJ/jg)	44.340	46.500
Kinematic viscosity. Cst at 40℃	2.52	2.0
Cetane number	51	55
Flash point, ℃	42	50
Fire point, ℃	45	56
Carbone residus, %	82.49	26
Sulphur content, %	0.030	0.045
Distillation temperature, ℃ at 58%	344	328
Distillation temperature, ℃ at 95%	362	340

burden of the government in disposing the waste, maintaining public sewers and treating the oily wastewater, but also lower the production cost of biodiesel significantly. Furthermore, biodiesel fuel has been demonstrated to be successfully produced from waste edible oils by an alkali-catalyzed transesterification process (Mittelbach and Gangl, 2001; Al-Widyan and Al-Shyoukh, 2001a, b), and can be considered as alternative fuels in diesel engines and other utilities (Dorado et al., 2003, 2004; Al-Widyan and Al-Shyoukh, 2002a, b).

Waste plastic oil

The last 30 years have witnessed an explosive growth of the plastic industry. The production of synthetic polymers represented by polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) worldwide has increased more than 100 times in the last three decades. These plastics are widely used in many important day to day applications such as clothing, household appliances and in automotive products and aerospace. While we enjoy the conveniences that plastics can provide, the treatment of waste plastics becomes an unavoidable and imminent issue. In this regard, it can be safely stated that we are in urgent need and effective ways to recycle waste plastics. Recently new ways of environmentally-friendly waste plastic recycling have been of interest, and among them, the use of waste plastics as a supplemental fuel with coal in the steel making industry has attracted interest (Mitsuhara et al., 2001). Attention is also focused on using oil derived from waste plastics in diesel engines. Diesel engines are the most preferred power plants due to their excellent driveability and higher thermal efficiency (Williams and Williams, 1990).

Plastics are non-biodegradable polymers mostly containing carbon, hydrogen and few other elements. According to a nationwide survey conducted in India in the year 2000 approximately 6000 tonnes of plastic wastes were generated every day, and only 60% of it was recycled. In India alone, the demand for plastics is about 8 million tonnes per year. More than 10,000 metric tonnes/ day are produced in India and balance is imported from other countries. Most of the plastics are recycled and sometimes it is not done so due to lack of sufficient market value. Of the waste plastics not recycled about 43% is polyethylene and most of them is in the form of containers and packaging materials (Mani and Nagarajan, 2009b).

The extent of conversion of plastics or plastic derived waxes into light engine fuels can be increased by the application of stable hydro cracking catalysts. Similar to petroleum derived cracking products, the fractions from plastics processing contain appreciable quantities of aromatics and unsaturated hydrocarbons (Hai et al., 2001). Some of the properties and characteristics of waste plastic oil and diesel are compared in Table 4. Because of the olefin content, it would be reasonable to submit the derived fractions to the hydrogenation step, typical of pyrolysis or cracking gasoline hydro refining process. Similarly, because of large quantity of linear n-paraffinic hydrocarbons it would be profitable to isomerise them in order to lower cloud and freezing points. The results showed that waste plastic disposal oil when mixed with heavy oils reduces the viscosity significantly and improves the engine performance (Soloiu et al., 2000). However, very little work has been done to test their use in high-speed diesel engines.

CONVERSION PROCESS

Conversion of waste engine oil

The high-volume waste oils can be turned into valuable fuel products by refining and treating processes. Converting of the waste oils into diesel and gasoline-like fuels to be used in engines without disposing is very

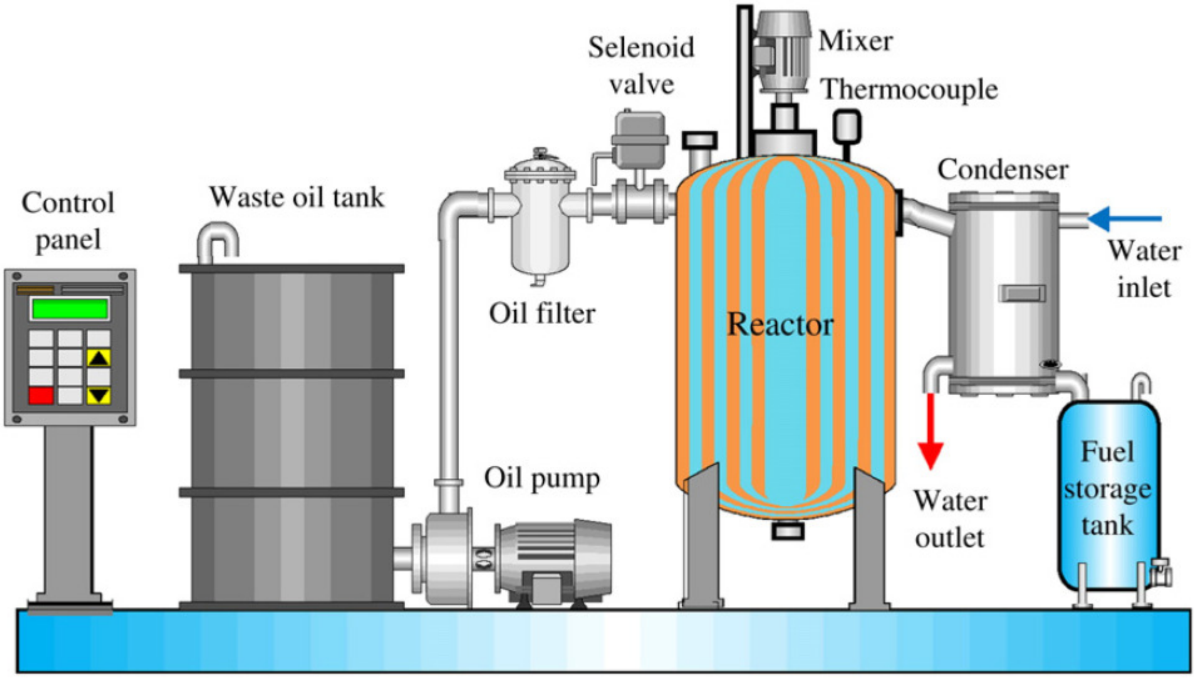

Figure 1. Schematic diagram of the purified and distillation system.

important (Arpa et al., 2010a, b). Utilization of the diesel and gasoline-like fuels produced from the waste lubricant oils, and blending of the produced fuels with gasoline or turpentine decrease consumption of petroleum based fuels, protecting environment from toxic and hazardous chemicals (Bhaskar et al., 2004). It also saves of foreign exchange, reduces greenhouse gas emissions and enhances regional development especially in developing countries (Demirbas and Demirbas, 2007). The turpentine is a biofuel obtained from the volatile fraction of resin extracted from pine trees. It has several advantages such as: a) it is a renewable and environmentally friendly alternative liquid fuel; b) its heating value and viscosity are higher than those of gasoline (Yumrutas et al., 2008; Karthikeyan and Mahalakshmi, 2007a, b); c) it can be used in any spark ignition (SI) engines as an additive to the gasoline (Yumrutas et al., 2008) or gasoline-like fuel (GLF); d) its self-ignition and boiling temperatures are higher than those of gasoline (Yumrutas et al., 2008; Karthikeyan and Mahalakshmi, 2007a, b). It can be produced from plentiful domestic cellulosic biomass resources such as woody plants, agricultural and forestry residues, and a large portion of municipal solid waste and industrial waste streams. It was used in early engines without any modification.

However, abundant availability of petrofuels stopped the usage of turpentine in internal combustion engines. Increasing cost of petrofuel prevailing today reopens the utility of turpentine in the internal combustion engines (Karthikeyan and Mahalakshmi, 2007a, b).

In the study of Arpa et al. (2010a, b) the authors used a recycling system for the waste lubricant oil. A recycling system was designed and manufactured in industry to purify waste oil from dust, small carbon soot and metal particulates, and reutilize the waste oil. Schematic representations and picture of the system are shown in Figure 1. In the recycling system, two fuels to be used in engines were produced by applying pyrolitic distillation. The fuels named as gasoline-like fuel (GLF) and diesel-like fuel (DLF) were obtained from waste lubrication engine oil. The oil was collected from gasoline and diesel engines. The recycling system was consisted of waste oil and produced fuel storage tank, pump, filter, a reactor, heaters, mixer, condenser and control unit. The waste lubricant engine oil was collected and stored in the storage tank. The oil pump was used to transfer waste oil in the storage tank to metallic filter. The waste oil was taken by the pump from the storage tank, and it was filtered using a quality filter with 20 mm mesh size to purify it from heavy metal particles, carbon soot, gum-type materials and other impurities. After removing the purified oil from the filter, it was flowed into the reactor.

The reactor is the most important part of the recycling system, since pyrolitic distillation or thermal treatment of the waste oil is performed in the reactor. It has a cylindrical shape with dimensions of 30 cm in diameter and 40 cm in height. It has a capacity that will be able to produce 20 L of fuel. This volume is enough to do all tests, which include characteristics of the fuel, performance and emissions. The reactor was isolated with glass wool with a thickness of 5 cm to minimize heat loss from the reactor. It includes a mixer and electrical heaters. The mixer was used to blend the oil and additive to obtain uniform blend and temperature in the oil. The heaters were used to heat the mixture of the purified oil and additive in order to make thermal destruction more easily. The heaters with a total heating capacity of 5 kW were placed around the reactor container. They can be capable of heating the mixture up to 600℃. They were controlled by a controlling unit adjusting heating rate. Then, the reactor was used as a heater of a distillation unit, and fuel sample produced from the waste lubricant oil in the reactor was distilled. The distillation unit was named as condenser, which is shown on Figure 1. After being condensed of the fuel sample was collected in the fuel storage tank. In the recycling system, 80 wt. % of the total, waste lubrication oil was converted into useful fuel in the pyrolysis process. Remaining parts such as impurities smaller than 20 mm, sludge and solid additives in the reactor were named as residue. It was about 20 wt. %, and was rejected from the reactor. It is necessary to purify the waste oil to produce a valuable fuel.

Therefore, it was taken from the tank by the oil pump, and was flowed through the filters having 20 μm mesh sizes. It was separated from dust, carbon soot, metal and other particles, and then charged to the reactor. The oil was heated up to 330℃ in the reactor, in which the pyrolysis process occurred, and it was treated for 1 h at this temperature. During the process, the mixer in the reactor mixed the oil-additive mixture. Heating process was continued by increasing the reactor temperature with electronic control unit in order to pass to the distillation process after the pyrolysis process. The vaporized fuel due to heating process was condensed through condenser in which water was used as cooling fluid. After the fuel become liquid, it was stored in fuel storage tank. Properties and distillation of the produced fuel should be tested to determine whether it can be used in a diesel engine or not, and they should also be compared with the diesel fuel commonly used in diesel engines (Table 1).

The produced fuel was segregated into light and heavy fuels according to characteristics and distillation test results, since some amount of the produced fuel was lighter than diesel fuel. That is why it was necessary to segregate the light fuel from the heavy fuel to eliminate detrimental effects of these fuels on an engine.

Conversion process of waste cooking oil

The conversion process presented in this section is the work of Xiangmei et al. (2008). The WCO was obtained from Restaurants. Every day this restaurant produces many WCO which used for frying beefsteak, French chips. So the WCO contain some food particles, phospholipids, grease and wax etc. WCO sample heated and filtered under vacuum to remove any different solid impurities. Then 40% phosphate acid washing and distillated water washing were adopted to eliminate phospholipids. And in order to avoid saponification reaction for high free fatty acid (FFA) content, the FFA was esterified with methanol by sulfuric acid. When the FFA content was lower than 1.0%, the sulfuric acid was drained and the sodium hydroxide was introduced into the system to complete the transesterification. Transesterification method was used for methyl ester production from waste frying oil. This method is a chemical reaction, which refers to the conversion of an organic acid ester into another ester of the same acid so-called biodiesel using an alcohol in presence of a catalyst. The method depends on several basic variables, namely, reaction temperature, alcohol and catalyst type. In this study per liter, waste frying oil requires 200 ml methyl alcohol, 6.5-8.5 g NaOH that is determined with titration, and 1-2 g acetic acid. In the first stage, test applied the transesterification reaction is realized in the reactor tank at 651℃ temperature during 1 h.

The second stage is composed of product rest and raw biodiesel separation from glycerin, then, washing process of obtained raw biodiesel is done by using the same volume of pure water, and second washing process follows and this washing process is carried out to increase the pellucidity of biodiesel by using bubble method. Lastly, water is separated from all products by evaporation with heating process (Zafer and Mevlüt, 2008) (Figure 2).

Conversion process of waste plastic oil

Pyrolysis

The technologies for WP recycling are grouped into three main categories: (1) material recycling, (2) chemical recycling, and (3) thermal recycling (or energy recovery). The primary and secondary recycling described above are considered material recycling; tertiary and quaternary recycling have the same meanings as chemical recycling and thermal recycling, respectively. Therefore, pyrolysis of plastics is considered tertiary recycling, which transforms the plastic polymers into their basic monomers or hydrocarbon (Lapuerta et al., 2002). The pyrolysis by direct heating (Figure 3) was adopted to produce the paraffin and crude oil from the plastic wastes in the 1990s. The pyrolysis process involves the break down of large molecules to smaller molecules. Produces hydrocarbons with small molecular mass (e.g. ethane) that can be separated by fractional distillation and used as fuels and chemicals. This process gives on weight basis 75% of liquid hydrocarbon, which is a mixture of petrol, diesel and kerosene, 5 to 10% residual coke and the rest is LPG (Mani and Nagarajan, 2009b).

The small-scaled process is featured by facilitation, convenience and low equipment investment. The system consists of feed-supply, pyrolysis reactor, fractionating tower, heating and temperature controller and device for

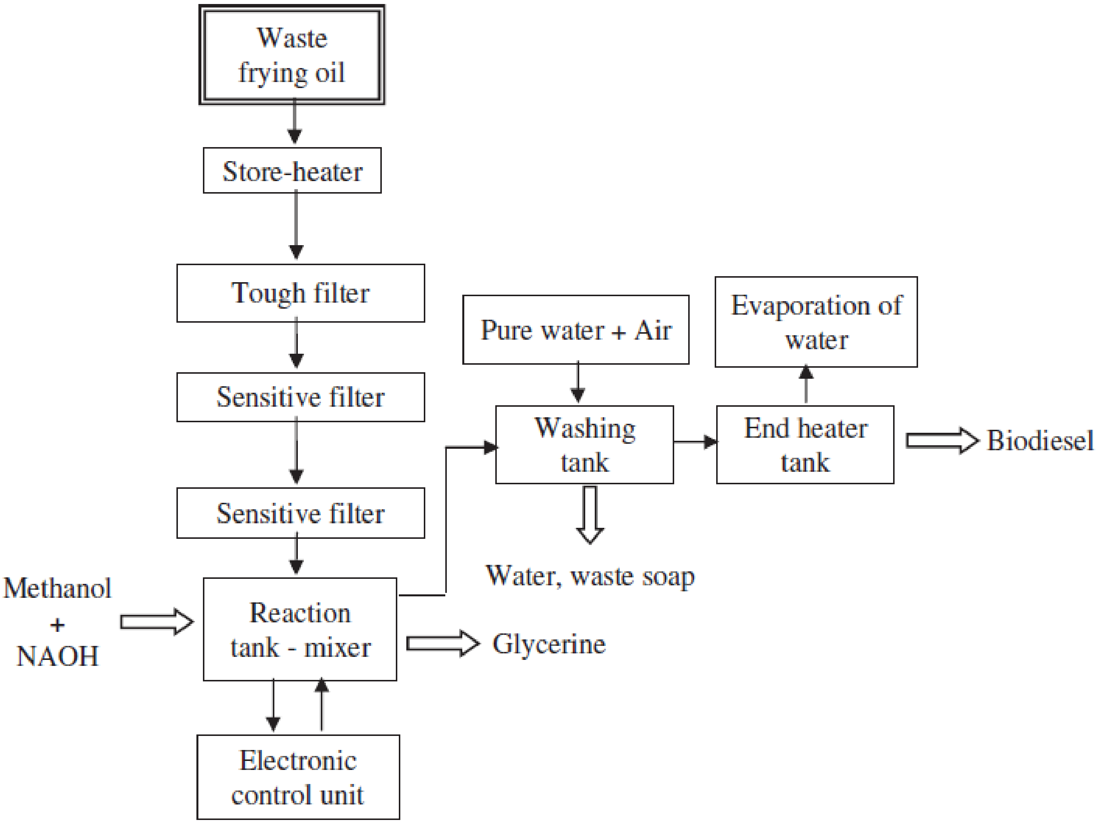

Figure 2. Schematic representation of biodiesel production system from waste frying oil.

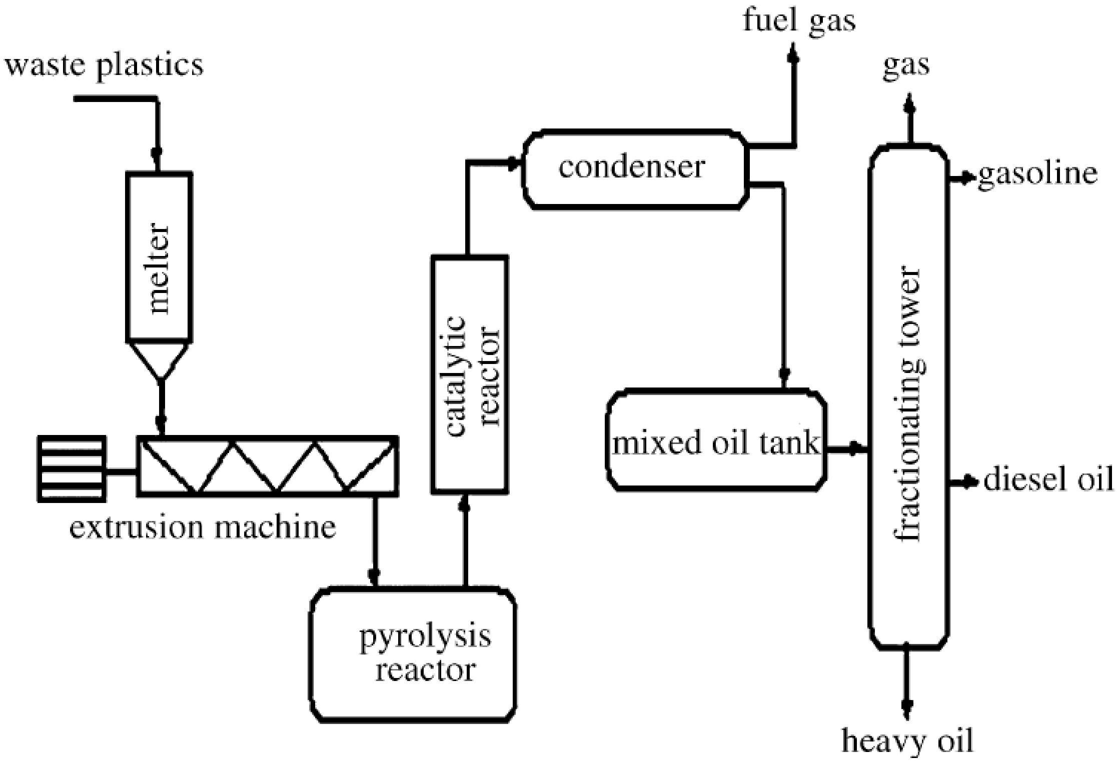

Figure 3. Pyrolysis-catalytic upgrades technique of plastic wastes.

filling the plastics into the pyrolysis reactor. The capacity of this pilot plant is 1000 tonnes/annum. However, the temperature caused by pyrolysis is higher and all the reactive time is longer than the other methods else. The octane number of gasoline gained is relatively low and the pour point of diesel oil is high. More paraffin is produced in the process of pyrolysis. Although this process is simple and convenient, the converting rate and yield is still lower (Guang-Hua et al., 2007).

The pyrolysis rate and yield should be promoted by a catalyst, like silica–alumina catalyst or diatomite, etc (Liu and Chen, 2001). Before the catalyst and plastic waste is mixed within the pyrolysis reactor, the plastic waste must be cleaned. The total yield of fuel oil is 50–65%, relying on the composition of plastic waste during pyrolysis. But, one problem is how to recycle the catalyst, carbon and other residua after pyrolysis. This process is also called the catalytic pyrolysis. The other problem for this process is the pyrolysis equipment's corrosion incurred by polyvinyl chloride (PVC) in mixed plastic wastes. Therefore, it is strongly recommended to establish a reasonable sorting system and apply a efficient technique to eliminate hydrochloric acid (Guang et al., 2007; Jerzy, 2002).

Pyrolysis-catalytic upgrade

Since the total yield of fuel oil with pyrolysis is still lower and the quality of oil is not satisfied as gasoline and diesel oil, the upgrade by catalyst for the crude products gained with pyrolysis can be used. Having improved the quality of finished oil, this process has been widely used in many factories (Li et al., 2002). Figure 4 shows the flowchart of pyrolysis-catalytic upgrade, which has been adopted in factories to treat the mixed plastic wastes. The system consists of the knapper, extrusion machine, pyrolysis reactor, catalytic upgrade reactor, fractionating tower, heating and temperature controller, separator of oil and water, and oilcan. The factory nearby Beijing used it to produce the fuel oil. The finished oil consists of gasoline (60%) and diesel oil (40%). The total yield reaches as high as 72.5% (Wang et al., 2003).

According to the yield of converting waste plastics to oil in China, the plastic wastes weighing 1.92 tonnes can produce 1 tonne of fuel oil. A plant with a capacity of 3 tonnes/day will need 1728 tonnes of plastic wastes annually. Supposing the average content of plastic wastes is that the municipal solid wastes account for about 0.5% for cities and 0.3% for countryside**,** the economic transportation distance will be within 200 km or so. As the economic support from local government is short, and the whole process from collecting, transporting, sorting to converting must be in accordance with marketing rule, the plant has to face towards a big risk in converting plastic wastes to fuel oil (Guang et al., 2007).

RESULTS OF USING WASTE OILS AS FUEL IN DIESEL ENGINES

Results obtained from waste cooking oil

Effect on performances

Studies demonstrate that WCO and its blends has a lower ignition delay (Enweremadu and Rutto, 2010; Rao et al., 2008; Sinha and Agarwal, 2005). A possible explanation for lower ignition delay periods of WCO and it blends with increase in the percentage of WCO might be due to higher octane number of WCO and its blends compared to diesel. Another possible explanation may be the presence of oxygen present in WCO and the splitting of higher molecules of WCO such as oleic and linoleic fatty acid methyl esters into lower molecules of volatile compounds during injection which advances the start of combustion causing earlier ignition. The reduction in ignition delay with increase in load might be as a result of higher combustion chamber wall temperature at the time of injection and reduced exhaust gas dilution (Enweremadu and Rutto, 2010).

The peak pressure of WCO fuel and its blends is higher than that of diesel fuel (Enweremadu and Rutto, 2010; Rao et al., 2008; Sinha and Agarwal, 2005). C. C. Enweremadu gives three reasons of this: The reduction in ignition delay with increase in percentage of WCO which results in earlier combustion might lead to the slightly higher peak pressures. Another possible explanation of this may be the higher oxygen content of WCO which favors better combustion. Also since WCO has lower calorific value, a large amount of fuel needs to be burned in premixed combustion stage and this may result in slightly higher peak pressure (Enweremadu and Rutto, 2010).

A detailed study on the effects of the percentage of used cooking oil methyl ester (WCO) on combustion characteristics (ignition delay, rate of pressure rise, peak pressure, heat release) has been undertaken (Rao et al., 2008) heat release of WCO and its blends were compared with that of diesel, the maximum heat release rate of 71.459 J/°CA was recorded for diesel at 68 BTDC, while WCO records 51.481 J/°CA at 88 BTDC. The results show that the maximum heat release rate decreases with increase in percentage of WCO in the blend. It can also be observed that maximum heat release rate occurs earlier with the increase in the percentage of WCO in the blend. The observations made for the rate of heat release may also be attributed to the reduction in ignition delay of WCO and its diesel blends and can be explained in a similar manner as the rate of pressure rise. Also, lower calorific value of WCO and its blends may contribute to lower heat release (Sinha and Agarwal, 2005). It is also possible that an increase in the oxygen fraction of the injected fuel provides an increase in the maximum heat release rate and in the fraction of

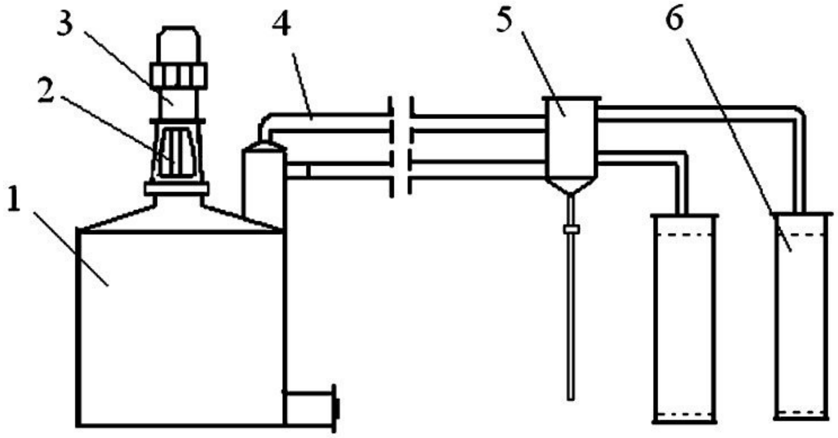

Figure 4. Flowchart of pyrolysis-catalytic upgrade (Pyrolysis equipment for mixure of plastic wase (1) Pyrolysis reactor; (2) Stirrer; (3) Motor; (4) Pipe; (5) Heavy oil separator; (6) Oil tank.

fuel burned in the premixed combustion phase; this case is more obvious at a high engine speed (Enweremadu and Rutto, 2010).

Effect on emissions

A relatively high disparity of results has been found regarding the emissions characteristics of used cooking oil biodiesel and/or its blends. Although, a dominant trend has been found in most cases, there have always been opposing trends proposed elsewhere by contrast. The precise features of the engines tested and their operating conditions, the different biodiesel fuels used, their characteristics, qualities and blends, measurement techniques and procedures, and instrumentations have a strong influence on the impact of WCO biodiesel hence, each study was specific (Enweremadu and Rutto, 2010).

Ulusoy and Tekin (2004) investigated the effects of biodiesel made from used frying oil on emissions in a Fiat Doblo 1.9 DS, four cylinder, four-stroke, and 46 kW power capacity diesel engine. Comparative measurements with diesel fuel were conducted on emission characteristics of each of the fuel used. According to emission tests, as a result of biodiesel consumption, a reduction of 8.59% in CO emission while an increase of 2.62 and 5.03% were observed in CO_2 emission and NOx emission, respectively. On the other hand, HC emissions and PM emissions decreased by 30.66 and 63.33%, respectively. It was concluded that these engine emission tests show that biodiesel is a more environment friendly fuel than diesel fuel.

Exhaust emission characteristics were evaluated in a Toyota van, powered by a 2 L indirect injection naturally aspirated diesel engine, operating on a vegetable-based waste cooking oil methyl ester by Gonzalez-Gomez et al. (2000). Tests were conducted on a chassis dynamometer and the data were compared with previous results conducted on the same vehicle using mineral diesel fuel. The data obtained included smoke opacity, CO, CO_2, O_2, NO, NO_2 and SO_2. These data showed that waste cooking oil methyl ester developed a significant lower smoke opacity level and reduced CO, CO_2, SO_2 emissions. However, NO_2, NO, and O_2 levels were higher with the waste vegetable oil based fuel (Gonzalez-Gomez et al., 2000).

The engine and road performance tests of biodiesel fuel derived from used cooking oil were evaluated in a Renault Mégane automobile and 75 kW Renault Mégane diesel engine in winter conditions for 7500 km road rests, and the results were compared with those using diesel fuel (Etinkaya et al., 2005). Results showed that the emission characteristics of biodiesel fuel produced from hazelnut soapstock/waste sunflower oil mixture and its blend with diesel fuel was investigated by Usta et al. (2005). The study showed that at full load, the CO emissions of the blend were higher at low speed and lower at high speeds than those of diesel fuel, while the blend resulted in higher CO_2 emissions in the experimental range. At partial loads, it was found that the blend did not cause significant changes in the CO and CO_2 emissions. There was a significant SO_2 reduction with the blends due to lower sulphur content of the biodiesel. NOx emissions slightly increased due to the higher combustion temperature and the presence of fuel oxygen with the blend at full load. However, the increasing amount of NOx emission slowed down with decreasing load. Most of the literature reviewed showed (Gonzalez-Gomez et al., 2000; Etinkaya et al., 2005; Usta et al., 2005) that there was a slight increase in NOx emissions when using WCO biodiesel. However, some other works found that NOx increased only under certain operating conditions such as test conditions, load conditions, alcohol-base of ester (methyl, ethyl) and the effect of WCO in the blends. While some works found reduction in NOx emissions when using WCO and its blends, other works did not find any differences in the NOx emissions between WCO and/or its blends and fossil diesel. Various reasons have been given for the increase in NOx emissions when using biodiesel and/or its blends. NOx emission is primarily a function of pressure, temperature and total oxygen concentration inside the combustion chamber. One argument is that the increases in NOx emissions obtained are in proportion to the concentration in biodiesel (Schumacher et al., 1994). It is has been argued that the increase in NOx emissions with increase in the percentage of WCO in the blend maybe associated with the increased oxygen content of WCO. Invariably all biodiesel have some level of oxygen bound to its chemical structures. Hence, oxygen concentration in WCO biodiesel fuel might have influenced the NOx formation.

Results obtained from waste engine oil

Effect on performances

Arpa et al. (2010a) conducted an experimental study on diesel-like fuel (DLF) on engine performance and exhaust emission. It is observed from the test results that about 60 cc out of each 100 cc of the waste oil are converted into the DLF. It is observed that the produced DLF can be used in diesel engines without any problem in terms of engine performance. The DLF increases torque, brake mean effective pressure, brake thermal efficiency and decreases brake specific fuel consumption of the engine for full power of operation.

The author found that T, Bmep, thermal efficiency and Bsfc trends for the DLF and diesel fuel are similar in nature. It is known that T and Bmep are directly proportional but Bsfc is indirectly proportional with the engine brake power given. The T, Bmep, and thermal efficiency values obtained for the DLF are slightly higher than those obtained for diesel fuel, but Bsfc is lower in all revolutions. Average increases of the T and Bmep values are approximately 0.69% for the DLF. This was due to high distillation temperature of the DLF than diesel fuel. In internal combustion engines, the T increases to a maximum point with the increase of engine speed. After that critical point, generally the torque decreases step by step (Mani and Nagarajan, 2009b). The maximum T and Bmep values obtained from the measured data for the DLF and diesel fuel in 2000 rpm are 33.86 and 33.71 Nm, 1048.21 and 1043.38 kPa, respectively. The corresponding thermal efficiency and Bsfc for the same fuels and the engine speed are 40.68 and 37.88%, 213.23 and 224.52 g/kWh respectively. After the maximum and minimum values of these parameters they decrease and increase with the engine speed gradually (Arpa et al., 2010a, b).

Cumali and Hüseyin (2011) conducted an experimental study on an alternative fuel performed by pyrolysis of waste vehicle tires. The authors used a pure DF and pure WEO and a mixture of them with different fractions. He found that power values of all fuel blends of WEO and diesel fuels showed increasing trends with respect to increase in engine speed. However, increases of power values have no linearity due to the increase in mechanical losses, especially in higher engine speeds. Power values of diesel operation were highest among all the test fuels. The higher the WEO amount blended in the fuel the lower the power of the engine at the corresponding condition of engine run. Namely, the lowest engine power values were obtained for the WEO100 fuel then for the WEO75 and WEO75 fuels, respectively. The reductions of power values of WEO and WEO blend fuels can be attributed to slightly lower calorific value of the WEO fuel. However, the differences in power values of test fuels were low at lower engine speeds. Especially, at the 1500 rpm of engine speed the power obtained for all test fuels was quite similar.

It is expected that the Bsfc should decrease when the brake power increases up to engine speed of 2200 rpm. At high speeds, friction, heat loses and deteriorating combustion increase Bsfc (Arpa et al., 2010a) performance parameters for the DGL are similar to those of diesel and are parallel to them in a regular way. Arpa found that the torque, Bmep, and thermal efficiency for the DLF ishigher than those of diesel while the Bsfc for the DLF is lower than that of diesel. This is an important criterion that makes the DLF advantageous.

Characteristics and distilled temperatures of fuels are the other effects on the performance parameters (Koç et al., 2009). The characteristics give better mixing and combustion characteristics of the fuels, which cause reduction in heat loss. It was also emphasized that higher distilled temperature gives better performance (Al-Ghouti et al., 2008; Koç et al., 2009). The distillation temperature make it possible to explain these differences in performance parameters. Diesel fuel is lighter than the DLF. Distillation temperatures of the DLF are higher than those of the diesel fuel up to 80 cc of 100 cc volume. This indicates that DF is a more volatile fuel than the fuel obtained from waste engine oil. High volatility decreases volumetric efficiency and cause vapor lock on hot climate conditions (48). When low volatile fuels or fuels distilled at higher temperatures are burned in combustion chamber of engine gradually, temperature and pressure in the combustion chamber will increase, which improves performance parameters of the engine (Al-Ghouti et al., 2008; Koç et al., 2009). As a result, ignition timing, air–fuel ratio, characteristics and higher distilled temperatures for the DLF give slightly better performance parameters than the diesel fuel. Therefore, T, Bmep and thermal efficiency increase and Bsfc decreases. Test results from the study have clearly shown that the DLF has a positive effect on the performance parameters of the engine, and it can be used as a fuel in the gasoline engine without any problems.

Cumali and Hüseyin (2011) found that the lowest torque values were obtained for WEO100, WEO75 and WEO50 fuels, respectively. The main reason of torque reduction is considered to be the slightly lower calorific value of the WEO fuel. Therefore, the reduction in the torque values of the WEO blends were linear with the WEO amount contained in the blend. The average bsfc of the test fuels obtained were 322.91, 322.81, 325.46, 325.86, 329.76, 333.64, 343.25, 354.21 and 367.17 gr/ kWh for diesel fuel, WEO5, WEO10, WEO15, WEO25, WEO35, WEO35, WEO50, WEO75 and WEO100 fuels, respectively. Bsfc is directly affected by the fuel consumption, power value at corresponding engine speed and calorific value of the fuel. Since the calorific value of blend fuels of WEO and diesel fuel is lower than that of diesel fuel bsfc values of WEO blends were lower than that of diesel fuels. The exhaust gas temperature values ever increased with the increase of the engine speed, for all the test fuels. The lowest exhaust gas temperature values were obtained for WEO100 fuel. The highest exhaust gas temperature values were observed for WEO5, WEO15 and diesel fuels. Exhaust gas temperature is affected by the combustion temperature, in-complete and retarded combustion. Lower exhaust temperature of the engine operation with pure WEO and WEO blend fuels can be attributed to all the reasons given above.

Effect on emissions

When the DLF sample is used, the exhaust temperature is higher than that of the diesel sample, and it increases with the engine speed. The measured exhaust temperature varied between 414 and 515°C for the DLF as compared to 397 and 477°C for diesel indicating remarkable variation in exhaust temperature. The higher values in temperatures for the DLF depend on the higher distillation temperatures, since any fuel distilled at higher temperature increases combustion temperature when it is combusted. As a result of the higher combustion temperature, exhaust gas temperature will increase. High temperatures in the exhaust are not desirable, for they cause higher energy transfer from the combustion chamber to the surrounding. High heat transfer decreases thermal efficiency of the engine at a finite value (Arpa et al., 2010a, b). Almost in all speeds of the engine the WEO100 gave the highest CO emission. At high speeds of the engine the lowest CO emissions were obtained from the diesel fuel. All the blend fuels of WEO and diesel fuel presented very similar CO emissions except for WEO100, WEO75 and WEO50. However, the increased engine speed caused to increase air movements in the engine cylinder which lead to more homogeneous air-fuel charge and thus resulted in an improved combustion and consequently lowered CO emissions. Therefore, when the engine speed increased CO emissions increased for all test fuels, especially WEO100 and WEO75 fuels (Cumali and Hüseyin, 2011; Arpa et al., 2010a, b).

The highest HC emissions were measured for WEO100 and following were WEO75 and WEO50 fuels, respectively. The lowest HC emissions were observed for diesel fuel, WEO5, and WEO10 fuels. However, the HC emissions for WEO25 and WEO35 fuels were quite lower than that of the WEO100 fuel, and were in acceptable values. Generally, WEO–diesel blends that contained high concentrations of WEO lead to a considerably high amount of HC emissions in the exhaust gasses. The main reasons, for increased HC and CO emissions for WEO fuels, are considered to be the poor atomization, lower cetane number and longer ignition delays. The higher density, of WEO caused more amounts of fuel to be injected in mass base, which lead to rich combustion condition is considered to be the most important reason of increased HC and CO emissions for WEO and blend fuels. Besides, the higher final distillation temperature of WEO might increase HC emissions. All these reasons which lead to incomplete combustion also lead to increased HC emission and CO emissions (Cumali and Hüseyin, 2011; Arpa et al., 2010a, b).

At the lower and medium speeds of the engine diesel fuel and blends of lower concentration of WEO resulted in a larger formation of NOx. It can be attributed to the higher combustion temperature with improved combustion. The lowest NOx emissions were obtained for WEO100 fuel at the lower speeds of engine operation. However, at the higher speeds of engine operation WEO100 fuel resulted in higher NOx emissions in comparison to other test fuels. The reason of this increase is considered to be the slower combustion of the WEO100 fuel that results in a larger period of combustion (Cumali and Hüseyin, 2011; Arpa et al., 2010a, b).

The amounts of SO_2 emissions found in the engine exhaust were almost linear with the WEO amount contained in the blend and considerably higher than that of diesel fuel since WEO contains a sulfur amount 4.5 times higher than that of diesel fuel. Therefore, it can be recommended that the sulfur amount of WEO fuel should be decreased (Cumali and Hüseyin, 2011; Arpa et al., 2010a, b).

Results obtained from waste plastic Oil

Effect on performance

From the study of Enweremadu and Rutto (2010); Mitsuhara et al. (2001); Williams and Williams (1990) and Mani and Nagarajan (2009b) it can be observed that the ignition delay of waste plastic oil is considerably longer than that of diesel. The longer delay period of waste plastic oil, results in a rise in-cylinder peak pressure. It may also be seen that the ignition delay is longer by about 2 to 2.5°CA for waste plastic oil than that of diesel and the peak pressure increases by 5 bar for waste plastic oil compared to diesel because of longer ignition delay.

Mani et al. (2009a), Mani and Nagarajan (2009b), Mani et al. (2011) found that the cylinder peak pressure for diesel is 67 bar at rated power and 71 bar in the case of waste plastic oil. Higher cylinder pressure in the case of waste plastic oil compared to diesel is due to the evaporation of waste plastic oil inside the cylinder by absorbing heat from the combustion chamber. Longer ignition delay at high load range increases the pressure of waste plastic oil than that of diesel. In other words, this period depicts the abnormal combustion or premixed combustion. However, this is the usual behaviour of high-octane fuel in high compression ratio engines. This can be controlled by proper selection of compression ratio (Mani and Nagarajan, 2009b). The authors studied the variation of cylinder peak pressure with brake power for waste plastic oil and diesel operation at different. They noticed that the cylinder peak pressure for the waste plastic oil is higher than the diesel. The cylinder peak pressure for diesel increases from 57 bar at no load to 67 bar at rated power and from 54 bar at no load to 71 bar at rated power in the case of waste plastic oil. In a CI engine, the peak pressure depends on the combustion rate in the initial stages, which is influenced by the amount of fuel taking part in the uncontrolled combustion phase that is governed by the delay period. It is also affected by the fuel mixture preparation during the delay period (Mani et al., 2009).

The maximum heat released in waste plastic oil is high compared to diesel. It can be noticed that in waste plastic oil, most of the heat release occurs only during the premixed combustion. Longer ignition delay results in higher heat release during the premixed combustion phase. The heat release rate is higher in the case of waste plastic oil due to the higher fuel-air ratio. The higher heat release rate leads to an increase in exhaust gas temperature (Enweremadu and Rutto, 2010; Mitsuhara et al., 2001; Mani and Nagarajan, 2009b).

Effect on emissions

Generally, compression ignition engine operates with lean mixtures and hence the CO emission would be low. CO emission is toxic and must be controlled (Mani et al., 2009a; Mani and Nagarajan, 2009b; Mani et al., 2011). It is an intermediate product in the combustion of a hydrocarbon fuel, so its emission results from incomplete combustion. Emission of CO is therefore greatly dependent on the air fuel ratio relative to the stoichiometric proportions. Rich combustion invariably produces CO, and emissions increase nearly linearly with the deviation from the stoichiometry (Murugan et al., 2005). The Concentration of CO emission varies from 14.14 g/kWh at 25% of rated power to 5.75 g/kWh at rated power for diesel, whereas it varies from 18.51 g/kWh at 25% of rated power to 6.19 g/kWh at rated power for waste plastic oil. The results show that CO emission of waste plastic oil is higher than diesel. The reason behind increased CO emission is incomplete combustion due to reduced in-cylinder temperatures. The drastic increase in CO emission at higher loads is due to higher fuel consumption (Mani et al., 2009a; Mani and Nagarajan, 2009b; Mani et al., 2011).

CO_2 varies from 1305.97 g/kWh at 25% of rated power to 789.36 g/kWh at rated power for diesel. It can be observed that in waste plastic oil it varies from 1163.25 g/kWh at 25% of rated power to 888.715 g/kWh at rated power. From the results, it is observed that the amount of CO_2 produced while using waste plastic oil is lower than diesel. This may be due to late burning of fuel leading to incomplete oxidation of CO (Mani et al., 2009a; Mani and Nagarajan, 2009b; Mani et al., 2011).

The formation of NOx is highly dependent on in-cylinder temperature, oxygen concentration and residence time for the reactions to take place. It can be noticed that the NOx emission increases in the waste plastic oil operation. NOx varies from 12.15 g/kWh at 25% of rated power to 7.91 g/kWh at rated power for diesel and from 14.68 g/kWh at 25% of rated power to 8.93 g/kWh at rated power for waste plastic oil. The reason for the increased NOx is due to the higher heat release rate and higher combustion temperature (Mani et al., 2009a; Mani and Nagarajan, 2009b; Mani et al., 2011).

Unburned hydrocarbon is a useful measure of combustion inefficiency. Unburned hydrocarbon consists of fuel that is incompletely burned. The term hydrocarbon means organic compounds in the gaseous state and solid hydrocarbons are the particulate matter (Mani et al., 2009a). At light load, large amounts of excess air and low exhaust temperature and lean fuel air mixture regions may survive to escape into the exhaust. Unburned hydrocarbon varies from 0.431 g/kWh at 25% of rated power to 0.1389 g/kWh at rated power for diesel. In the case of waste plastic oil it varies from 0.4393 g/kWh at 25% of rated power to 0.147 g/kWh at rated power. From the results, it can be noticed that the concentration of the hydrocarbon of waste plastic oil is marginally higher than diesel. The reason behind increased unburned hydrocarbon in waste plastic oil may be due to higher fumigation rate and non-availability of oxygen relative to diesel (Mani et al., 2009a; Mani and Nagarajan, 2009b; Mani et al., 2011).

CONCLUSION

This paper gives a brief review on the conversion process of the most waste oils available in now days in order to use them in Diesel Engine. From the results obtained from various studies we can summarize the following points:

(i) Results from using waste cooking oil as fuel for diesel engines showed that the fuel obtained has a higher viscosity and lower calorific value; this will have a major bearing on spray formation and initial combustion. The ignition delay of UCO biodiesel decreases. The peak pressure of UCO biodiesel and its blends is higher than that of diesel fuel. WCO showed a higher exhaust gas temperature compared to diesel fuel. Increased oxygen content which improves combustion is a reason given for this. A relatively high disparity of results has been found regarding the emissions characteristics of used cooking oil biodiesel and/or its blends. Most of the reports recorded slight increases in NOx when compared to diesel at rated load. The reasons most frequently given include higher oxygen content of biodiesel and its blends and advanced injection process with biodiesel. CO and unburned HC emissions were found to significantly decrease with biodiesel and its blends due to a more complete combustion caused by higher oxygen content.
(ii) Engine was able to run with 100% waste plastic oil.Ignition delay was longer by about 2.5℃A in the case of waste plastic oil compared to diesel. NOx is higher by about 25% for waste plastic oil operation than that of diesel operation. CO emission increased by 5% in waste plastic oil compared to diesel operation.Unburned hydrocarbon emission is higher by about 15%. Engine fueled with waste plastic oil exhibits higher thermal efficiency upto 75% of the rated power.
(iii) Fuel obtained from waste engine oil can be used as fuel in diesel engines without any problems in terms of engine performance. The thermal and physical characteristics of the DLF are close to those values of a typical diesel sample. Moreover, its distillation temperature increases gradually, and its behavior is similar to that of diesel fuels used in engines. When the DLF was used, it was observed that torque, brake mean effective pressure and brake thermal efficiency were higher than those of the diesel sample while the brake specific fuel consumption was lower.

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