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Analysis of Flue Gas Emissions Using a Semi-industrial Boiler Fueled by Biodiesel Produced from Two-stage Transesterification of Waste Cooking Oil

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In this work, waste cooking oil and methanol as feedstock together with sulfuric acid and potassium hydroxide as catalysts were used to produce biodiesel. The physical properties of the waste cooking oil, the produced biodiesel and the purchased petrodiesel were measured using specified ASTM standards. To examine their performance and their flue gases emissions, biodiesel and petrodiesel were burnt in a wet base semi-industrial boiler. The emitted combustion gases, including CO, NO_x, SO_2 and CO_2, were measured with a flue-gas analyzer at a wide range of air-to-fuel ratios and two levels of energy. For better reliability, all tests were repeated five times and almost no measurable differences were found in the repeat tests. The results show that produced biodiesel meets ASTM standards for flash point, heating value, specific gravity, kinematic viscosity, copper corrosion, acid number, cetane number, carbon residue, and total sulfur. These properties of biodiesel are also comparable with the petrodiesel properties. The trends of exhaust temperature and combustion efficiency of biodiesel are the same as petrodiesel at different air-to-fuel ratio. However, they are slightly lower. The CO, NO_x, SO_2 and CO_2 emissions of biodiesel are lower than those of petrodiesel at different air-to-fuel ratios and two levels of energy.

Key words:
Biodiesel, combustion efficiency, emission, renewable energy, waste cooking oil

Introduction

Today, the world energy demand is increasing so rapidly due to growing industrialization and population that the limited reservoirs will soon be depleted at the current rate of consumption. Petroleum is a non-renewable energy resource, which means that resources of this type of fossil fuel are finite and will come to an end upon continuous usage. According to the Oil and Gas Journal, at the beginning of 2004, worldwide reserves were estimated at 1.27 trillion barrels of oil, and 6,100 trillion cubic feet of natural gas. At today's consumption level of about 85 million barrels per day of oil, and 260 billion cubic feet per day of natural gas, the reserves represent a 40-year supply of oil and a 64-years supply of natural gas.[1] Both the shortage of resources and increasing petrol prices have led to finding new alternative and renewable energy resources. In addition, environmental issues drive the development of alternative energy resources, since fossil fuel combustion causes various environmental problems including global warming, air pollution, acid precipitation, ozone depletion, forest destruc-

tion, and emission of radioactive substances.[2] Alternative energy resources include hydro, wind, solar, geothermal, hydrogen, nuclear, and biomass energy.[3] Biofuel derived from biomass is considered the most promising alternative fuel resource because it is renewable and environmentally friendly. Biofuel can be defined as any liquid or gaseous fuel that can be produced from biomass, including biodiesel, alcohol and biogas.[4] Biodiesel can be produced from methanol, ethanol and vegetable oils which are agriculturally derived products. Compared to petrodiesel, biodiesel has many advantages such as lower flue gas emission, it is biodegradable, renewable, and has superior lubricating properties.[5]

Currently, the cost of this fuel is a primary factor that limits its use. Preliminary studies of the potential for biodiesel production have indicated that small-scale biodiesel plants based on purified oil are unsustainable because of the high cost of raw material. However, one way to reduce the cost of biodiesel is to use a less expensive form of vegetable oil such as waste oils, greases and soap stocks,[6–21] since feedstock costs account for more than 85 % of the total cost of biodiesel production.[22–23] Many reports are available on the use of waste cooking oil for biodiesel production.[24–26]

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Waste cooking oil (WCO) cannot be directly used in diesel engines because of its high viscosity, which poses many problems to fuel injection. There are a number of ways to reduce the viscosity of waste cooking oils. Dilution, micro-emulsification, pyrolysis, and transesterification are four techniques applied to solve the problems encountered with high fuel viscosity. One of the most common methods used to reduce oil viscosity in the biodiesel industry is called transesterification.[27] In the transesterification of vegetable oils, a triglyceride reacts with an alcohol in the presence of a strong acid or base, producing a mixture of fatty acid alkyl esters and glycerol.[28–29] Alcohol reduces the viscosity of the oil in transesterification. In this study, we used methanol, which has the lowest viscosity among alcohols and good equilibrium conversion.

Many researchers investigated the key reaction conditions and parameters of alcoholysis of triglycerides. Zheng *et al*.[10] studied the reaction kinetics of acid catalyzed transesterification of waste frying oil. They found that at the methanol/oil molar ratio of 250:1 at 70 ºC or in the range 74:1–250:1 at 80 ºC, the reaction was a pseudo-first order reaction. High yield of 99±1 % could be achieved at both 70 ºC and 80 ºC and a stirring rate of 400 rpm, using feed molar ratio oil: methanol: acid of 1:245:3.8. In contrast, Wang *et al*.[11] investigated a two-step catalyzed processes for synthesis of biodiesel by using WCO from Chinese restaurants. In the first step, ferric sulfate-catalyzed methanolysis was carried out, while potassium hydroxide catalysis was performed in the second step. The authors concluded that, compared with one-step sulfur acid catalysis, the two-step catalyzed process provided a simpler and more economic method of producing biodiesel from WCO.

The optimum conditions developed for production of good quality biodiesel from used sunflower oil were: molar ratio of methanol to oil 6.825:1, catalyst concentration of 0.679 wt %, stirring speed of 290 rpm and a reaction time of 2 h.[30] The alkali-catalyzed transesterification can be completed at low temperatures and pressures with high conversion rates, meaning lower operating costs of alkali-base method compared with other methods.[31] Excess catalyst was used to neutralize free fatty acids (FFA) present in waste cooking oil. A process was developed by Canakci where the high FFA feedstock was initially treated using acidic catalyst to reduce FFA level below 1 %. Pre-treated feedstock with FFA less than 1 % was then transesterified with methanol using alkaline catalyst. It was observed that two-step acid catalyzed esterification followed by alkaline catalyzed reaction improved ester yield.[6]

The main objective of this study was to produce a renewable fuel from almost worthless feedstock that contributes to the control of gas emissions with almost the same performance of fossil fuel. Specifically, waste cooking oil collected from the restaurant of the Petroleum University of Technology (PUT) was esterified to reduce free fatty acids (FFA) to below 1 %. Transesterification of waste cooking oil with lowered FFA was then performed with methanol. KOH was used as catalyst in this reaction. Biodiesel was produced as an upper layer of transesterification products. Physical properties of waste cooking oils, produced biodiesel and purchased petrodiesel were measured using specified standards. The physical properties of the biodiesel and petrodiesel were compared. To examine their performance and flue gases emissions, biodiesel and petrodiesel were burnt in a wet base semi-industrial boiler. The emitted combustion gases, including CO, NO_x, SO_2 and CO_2, were measured with a flue-gas analyzer. Finally, the effects of air-to-fuel ratio on performance and emitted gases of the biodiesel and petrodiesel at two different energy levels were investigated.

Experimental

Experimental procedures include procedures for biodiesel production, physical properties ASTM tests and combustion in a semi-industrial boiler. Tests were carried out in the laboratories of PUT and Abadan's refinery. Esterification and transesterification reactions were accomplished in the gas research laboratory of PUT. Physical properties of waste cooking oil, biodiesel and petrodiesel were measured in Abadan oil refinery laboratory. The combustion test was carried out in the heat transfer laboratory of PUT.

Raw material

Waste cooking oil collected from the restaurant of the Petroleum University of Technology (PUT) and methanol, potassium hydroxide and sulfuric acid provided from Merck Company, were the raw materials used in this study. Silica gel purchased from a local shop was used as drying agent.

Apparatus

LR 2000P modularly expandable laboratory reactor was used for transesterification. The reactor was double-walled, jacketed with 2 liter vessels made of stainless steel, with bottom discharge valve. A Eurostar power control-visc P7 overhead stirrer with 8 to 290 rpm was used. The combustion study was accomplished on a fully instrumented water-jacketed combustion chamber equipped with a sterling 90UK Spec liquid fuel burner. This combustion chamber is a stainless steel horizontal cylinder, one meter in length, with an inner diameter of 45 cm and outer diameter of 0.50 m.

In addition to the standard analysis, the KANE QUINTOX 9106 flue-gas analyzer equipped with electrochemical cells, allowed us to investigate CO, NO and SO_2 in the exhaust stack.

Composition analysis of waste cooking oil

Table 1 shows the chemical properties and fatty acid composition of WCO. Fatty acid (FA) is a carboxylic acid with a long aliphatic chain, and these long-chain FAs generally have an even number of carbon atoms. They may be saturated (e.g. palmitic acid and stearic acid) or unsaturated, with one double bond (e.g. oleic acid) or two or more double bonds, in which case they are called polyunsaturated FAs (e.g. linoleic acid and linolenic acid).

Table 1 – *Fatty acid composition of waste cooking oil*

Fatty acid	Waste cooking oil (wt %)
Palmitic acid C16:0	12
Palmitoleic C16:1	2.8
Stearic acid C18:0	4.7
Oleic acid C18:1	58.7
Linoleic acid C18:2	26.3
Arachidic C20:0	0.9
Eicosenoic C20:1	1.9

WCO has higher specific gravity relative to purified oil because it has much residue such as water, because water is mixed inside the WCO as a result of condensation of the cooking process. Therefore, the density of WCO is higher compared to refined oil.

Biodiesel production

Pre-treatment of WCO

The WCO collected from the restaurant of the Ahwaz Faculty of Petroleum Engineering was contaminated with water, solid particles, FFA and many other impurities. Due to the very high temperature during the food frying process, chemical reactions such as hydrolysis, polymerization and oxidation will occur, which can increase the FFA level. To reduce the FFA of WCO, it should be esterified before transesterification by one acidic catalyst to avoid saponification problems. Water also creates a problem such as foaming during transesterification. WCO was mixed with silica gel (10 weight percent, 50 meshes) to remove water content by stirring the mixture and vacuum filtration for the removal of silica gel. Solid particles of waste cooking oil were filtered with a No. 40 Quantitative.

Esterification

In order to reduce the FFA of WCO, before transesterification it should be esterified with one acidic catalyst to avoid saponification problems. Two liters of WCO was poured into the batch reactor. Two weight percent of sulfuric acid as a catalyst was mixed with 3.4:1 molar ratios of methanol to oil and mixed vigorously. The solution was then poured into the WCO and left to react at 48 °C for 2 h with 290 rpm. When the reaction was completed, a thick layer of soap formed which interfered with the glycerol separation.

Transesterification

Waste cooking oils were converted into biodiesel by alkali-catalyzed transesterification reaction. In the alkali catalytic transesterification method, the catalyst is dissolved in methanol by vigorous stirring in a batch reactor. Transesterification reactions were carried out at optimum conditions mentioned by Mansourpoor and Shariati,[30] 6.8:1 molar ratios of methanol to oil, 48 °C reaction temperature and 0.7 wt % of alkali catalyst concentration (excess catalyst was used about 0.8 wt % for waste oil). Many researchers have reported the optimal conditions for the alkali-based approach.[6,32–37] The anhydrous waste oil which esterifies one stage was poured into the reactor and allowed to equilibrate to the temperature of reaction (heated to 48 °C) at 290 rpm. The hot water circulating in the jacket of the reactor provided the necessary heat for reaction. The catalyst was dissolved in methanol and then added to the waste cooking oil. The final mixture was stirred vigorously for 2 h at 48 ºC in atmospheric pressure.

A successful transesterification reaction produces two liquid phases. Glycerin has a higher density relative to biodiesel and goes to the bottom of the funnel separator after hours. Phase separation could be observed within 15 minutes and could be completed within 4 h of settling. After glycerin drainage, the biodiesel was washed out from impurities and un-reacted agents with warm water. Finally, the biodiesel was dried with silica gel (10 weight percent, 50 meshes) to remove water content by stirring the mixture and vacuum filtration for the removal of silica gel.

Operating conditions

Combustion tests were carried out in a semi-industrial boiler at steady state conditions that permitted good repeatability. All fuels were tested under the same operating conditions, which were defined by setting fuel pressure, fan damper setting, and choosing a nozzle. Air to fuel ratio and fuel pressure could be varied by the user.

Results and discussion

Transesterification of WCO with methanol was carried out in LR2000P reactor, using KOH as catalyst. Table 2 presents operating conditions and yield of biodiesel.

Table 2 – *Operating conditions and yield of biodiesel*

Operating conditions				Yield (%)
MeOH (mL)	KOH (g)	Oil (L)	T (°C)	
500	17.5	2	48	97.4

Physical properties

Physical properties of biodiesel such as flash point, cetane index, heating value, viscosity, etc., were determined with the methods given in Table 3.

Table 3 – *Standard methods applied for biodiesel properties*

Physical property	Test method
Flash Point	ASTM D 93
Cetane Index	ASTM D 976
Heating Value	ASTM D 240
Viscosity	ASTM D 445
Specific Gravity	ASTM D 1298
Copper Strip Corrosion	ASTM D 130
Cloud Point	ASTM D 2500
Pour Point	ASTM D 97
Acid Number	ASTM D 974
Water and Sediment	ASTM D 2709
Carbon Residues	ASTM D 198
Total Sulfur	UOP 357

The physical properties of the biodiesel produced at the laboratory were measured in Abadan's oil refinery laboratory, and are given in Table 4. It was observed that the biodiesel had higher flash point relative to petrodiesel, which is several times better than petrodiesel at 65 °C. Therefore, it is safe to be shipped by common mail carriers. A higher cetane number indicates greater fuel efficiency.[38] In this work, biodiesel had a higher cetane number than petrodiesel because of its oxygen content. The higher cetane number leads to easier start of combustion, runs better, and burns cleaner. Total sulfur of biodiesel was low; therefore the SO_2 emission of its combustion is very low.

Table 4 – *Physical properties of biodiesel and petrodiesel*

Test	Methyl ester	Petrodiesel	ASTM
Flash Point (°C)	190	65	min 130
Cetane number	54.2	min 51	min 51
Heating Value (MJ kg^{-1})	39.5	45.4	37.6–40.5
Viscosity at 40 °C (Pa s)	0.0037	0.0017–0.00343	0.0017–0.0053
Specific Gravity	0.886	0.857	0.880
Copper Strip Corrosion	1a	1a	No. 3 max
Cloud Point (°C)	0	–6	N/A
Pour Point (°C)	–4	–19	N/A
Acid Number (mg KOH g^{-1})	0.255	0.002	0.800
Water and Sediment	Trace	Trace	0.005
Carbon Residues (wt %)	0.004	max 0.01	max 0.05
Total Sulfur (ppm)	1.4	50–500	15

In the petroleum industry, cloud point refers to the temperature below which wax in fuel forms a cloudy appearance. Pour point is the lowest temperature at which the oil specimen can still be moved. Table 4 shows cloud and pour points of ester. In this work, cloud point of biodiesel is 0 °C while pour point is –4 °C. It was found that biodiesel had higher cloud point than petrodiesel because the biodiesel produced from waste cooking oils contained FFA. FFAs increase the cloud point of biodiesel.

After transesterification, the biodiesel showed substantial reduction in viscosity which met the ASTM standard (0.0017 – 0.0053 Pa s). In this work, viscosity of the biodiesel was 0.0037 Pa s, while that of petrodiesel was lower (0.0017 – 0.00343 Pa s).

Acid number is the mass of potassium hydroxide (KOH) in milligrams that is required to neutralize one gram of chemical substance. Acid value of crude WCO was very high (12 mg KOH g^{-1}) and acid value of esters after transesterification was lower than the limit of ASTM standard (max 0.8). The acid number of methyl ester was reduced to 0.255 mg KOH g^{-1}. Acid numbers higher than 0.50 have been associated with fuel system deposits and reduced life of fuel pumps and filters.

Biodiesel generally has a lower heating value than petrodiesel. Heating value of ester is 39.5 MJ kg^{-1} which is not much different from that of waste cooking oil. These values were approximately 12 % less than those of petrodiesel reported in references.

Table 4 shows that methyl ester meets ASTM standards for flash point, heating value, specific gravity, kinematic viscosity, copper corrosion, acid number, cetane number, carbon residue and total sulfur.

Boiler performance and specifications

To examine the fuels' performance and emissions, a wet base semi-industrial boiler was used. Specifications of the boiler are given in Table 5.

Table 5 – *Specification of boiler C492 P.A. Hilton*

Net Weight	175 kg
Dimensions	Height: 1.700 m – Depth: 2 m – Width: 0.8 m
Packing Volume:	3.96 m³
Fuel	Kerosene, gas oil or other clean light fuels
Fuel density	790 – 835 kg m^{-3}
Fuel viscosity	0.011–0.055 cm^2 s^{-1} at 40 °C
Fuel flow rate	2 to 5 g s^{-1}
Water flow meter	100 to 400 g s^{-1}
Temperature	0 to 1100 °C
Electrical Specification	Either: **A**: 220–240 V, Single Phase, 50 Hz (With earth/ground) **B**: 110–120 V, Single Phase, 60 Hz (With earth/ground)

The flame burns within a stainless steel combustion chamber (0.45 m diameter and 1 m length) which is water cooled and of sufficient size to prevent flame impingement under normal conditions. The flame was observed through four 0.1 m diameter windows. The burner had adjustable air settings for different air-to-fuel ratios. Cooling water inlet and outlet temperature, air inlet temperature, exhaust temperature, flame temperature, cooling water flow rate, fuel flow rate, and mass flow rates of air and fuel were read from the control panel. Fuels were burned at two fuel pressures of 8 and 11 bar. Average fuel consumption at 8 bar was 5.68 L h^{-1} for biodiesel, and 5.4 L h^{-1} for petrodiesel. At 11 bar, 6.12 L h^{-1} petrodiesel and 6.42 L h^{-1} biodiesel were consumed. Combustion efficiency of the boiler was calculated by using the inlet and outlet water temperatures, heating value of fuel, and flow rates. In this work, combustion efficiency and emissions of biodiesel were compared to those of petrodiesel. For every set of experimental test, temperature and emissions readings were recorded after steady-state combustion was achieved as indicated by stable exhaust gas and water outlet temperature values. Specifications of Quintox gas analyzer are given in Table 6.

Table 6 – *Specification of Quintox KM9106 gas analyzer*

Parameter	Resolution	Accuracy	Range
Temperature of exhaust gas	0.1 °C/F	±1 °F/C, ±0.3 % of rdg	0 ° to 1170 °C
Nitric Oxide (NO)	1 ppm	±5 ppm <100 ppm	0–5000 ppm
Carbon Monoxide (CO)	1 ppm	±20 ppm <400 ppm	0–10000 ppm
Oxygen (O$_2$)	0.1 %	–0.1 %+0.2 %	0 to 25 %
Carbon Dioxide (CO$_2$)	0.1 %	± 0.20 %	0-fuel value
Sulfur Dioxide (SO$_2$)	1 ppm	±5 % of reading >100 ppm	0–5000 ppm
Dimensions	17.75" long x 9" wide x 13.75" high		
Weight	21 lbs		

Exhaust temperature

Figs. 1 and 2 depict the variation of exhaust temperature (T_{exh}) with Air to Fuel (A/F) ratio. The T_{exh} for biodiesel varied between 560 to 615 °C at 8 bar, and 610 to 655 °C at 11 bar. Exhaust gas temperature of petrodiesel varied from 596 to 637 °C at 8 bar, and 645 to 709 °C at 11 bar. As fuel pressure increased, so did flue gas temperature of biodiesel
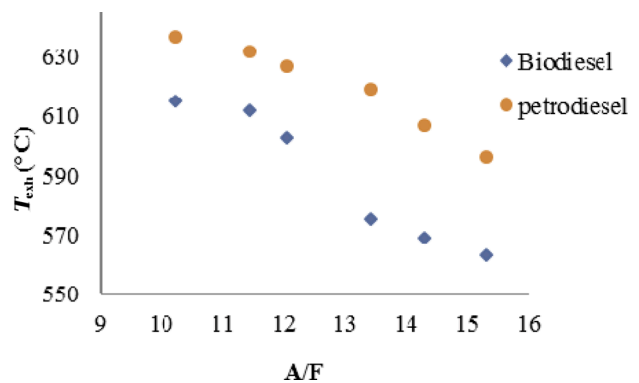

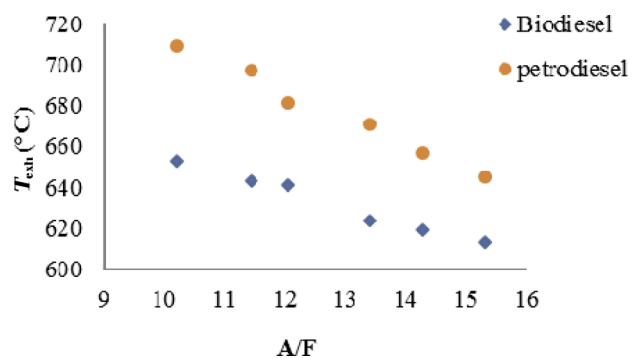F i g . 1 – T_{exh} *(°C) vs. A/F ratio at 8 bar*

F i g . 2 – T_{exh} *(°C) vs. A/F ratio at 11 bar*

and petrodiesel. Petrodiesel had higher exhaust temperatures relative to biodiesel because of its lower mass flow rates and higher heating value. Tashtoush *et al.*[39] also reported higher exhaust temperature of petrodiesel than that of biodiesel although the fuels had been injected at equal fuel pressure into the boiler. Variation of T_{exh} with A/F ratio was different from variation of T_{exh} with fuel pressure. At lower A/F ratios, T_{exh} of biodiesels and petrodiesel were closer than at higher A/F. Figs. 1 and 2 show that the exhaust gas temperature decreases as A/F ratios increases. Decrease in exhaust gas temperature with increasing A/F ratios is related to two effects. The first is the entering of excess air into the boiler which is colder than the gases in it, and the second is that the heat generation in the system is constant while it is distributed as measurable heat between circulating water in the boiler and the gases leaving the boiler. Despite these results, Batey *et al.*[40] reported no significant difference in the exhaust gas temperature of biodiesel compared with petrodiesel.

Combustion efficiency

The combustion efficiency, η_c, is the ratio between the heat transferred to the water in the jacket of the boiler, Q_w, and the amount of heat input to boiler, Q_{in}. Figs. 3 and 4 present the variation of com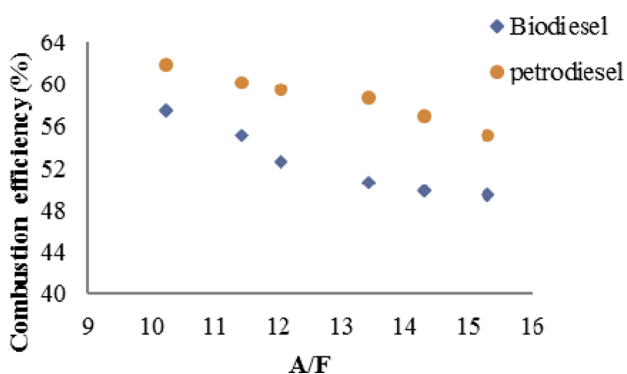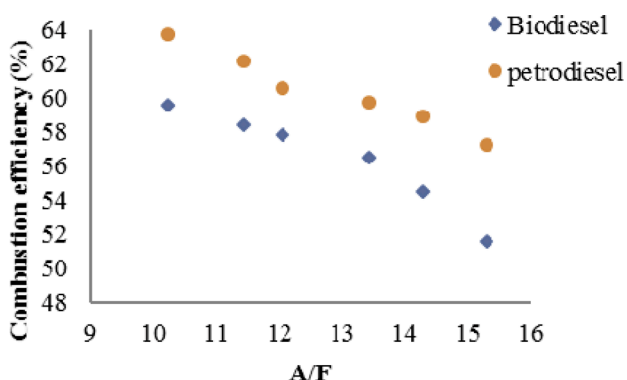bustion efficiency in relation to A/F ratio at two fuel pressures. By increasing the A/F ratio, the temperature of the flame was decreased; hence, the difference between cooling water temperature and flame temperature resulted in the reduction of Q_w which consequently leads to lower system efficiency. The combustion efficiencies increased as the fuel pressure increased. This trend was observed due to the fact that rising fuel pressure enhanced the spray characteristics of the fuels.

Figs. 3 and 4 indicate that petrodiesel performed a little better, but only by 4.41 to 5.68 %. The probably reason being the lower density and viscosity of petrodiesel compared to biodiesel, which in turn may have better mixability and uniform distribution in the flame.

Emissions

NOx

Figs. 5 and 6 show the measured emissions of nitrogen oxides (NO_x) for fuels at 8 and 11 bar. The use of biodiesel in diesel engines often led to an increase in NOx emissions[41–46] while various results were obtained in boilers.[42,47–54] When biodiesel is burnt in boilers, NO_x tends to decrease because the combustion process is different than that in engines (open flame for boilers, closed cylinder with high-pressure spray combustion for engines).[55] The
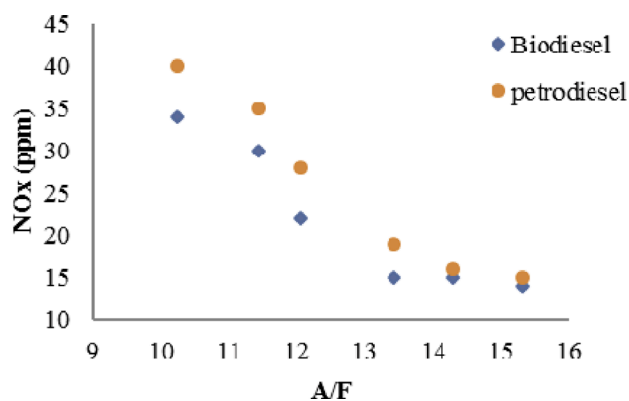

F i g . 3 – *Combustion efficiency (%) vs. A/F ratio at 8 bar*

F i g . 5 – *NO_x (ppm) vs. A/F ratio at 8 bar*

F i g . 4 – *Combustion efficiency (%) vs. A/F ratio at 11 bar*
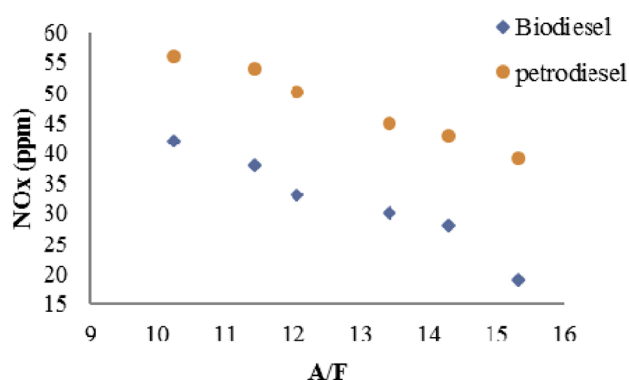

F i g . 6 – *NO_x (ppm) vs. A/F ratio at 11 bar*

formation of NO_x depends mainly on the percentage of oxygen and exhaust gas temperatures. By increasing the exhaust gas temperature and the oxygen of the boiler, the NO_x was increased. By increasing the A/F ratio, since a higher amount of air entered the boiler and entrance heat was constant, the exhaust temperature was reduced and hence NO_x was reduced in the flue gases. Many researchers[39,56,57] reported a reduction in NO_x emissions with the use of biodiesel compared with petrodiesel in a wide range of A/F at two different energy rates of a boiler.

Petrodiesel has higher NO_x relative to biodiesel at 11 bar, but had the fuel had been injected at 8 bar, this amount would be the same for both petrodiesel and biodiesel.

CO

Figs. 7 and 8 show the measured emissions of carbon monoxide (CO) with A/F ratio for fuels at 8 and 11 bar. It was seen that biodiesel emits less pollutants than petrodiesel. The higher concentration of CO for petrodiesel is due to the higher carbon content by weight of petrodiesel relative to biodiesel.[43,57–58] The high flow rate of entrance air extinguished the flame and led to poor distribution of the fuel in the chamber. Furthermore, the high air to fuel r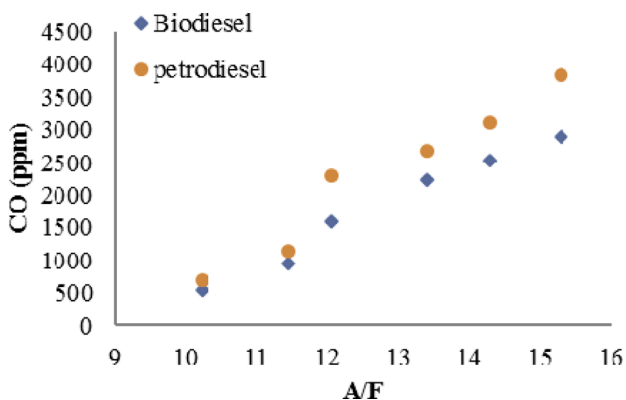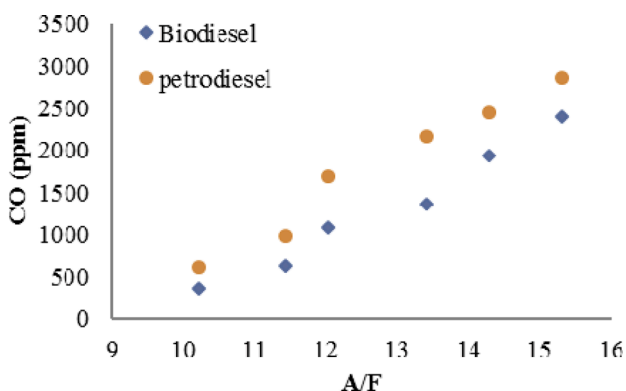atio led to a decrease in flame temperature which in turn led to incomplete and unstable fuel combustion. Consequently, the high fuel pressures and low A/F ratio led to improvement in combustion of biodiesel and petrodiesel in the boiler. At constant A/F, the amount of CO was reduced with the use of biodiesel by about 16.3 to 41.8 % at 11 bar, and 22.8 to 27.1 % at 8 bar relative to petrodiesel.

CO_2

Figs. 9 and 10 show variation of CO_2 vs. A/F ratio for fuels at 8 and 11 bar. These figures show that a reduction in CO_2 of 11 to 56.4 % at 8 bar, and 36.7 to 46.62 % at 11 bar is attainable if biodiesel is burnt instead of petrodiesel under the same conditions. Petrodiesel emitted higher amounts of CO_2 when compared to biodiesel at different A/F ratios and two fuel pressures of the boiler, which make biodiesel more suitable for boilers than petrodiesel. Higher CO_2 in petrodiesel combustion is due to the higher carbon content of petrodiesel relative to biodiesel. Biodiesel releases only the CO_2 that was absorbed by the plants as they were growing and making oil. With increasing A/F ratios, the percentage of CO_2 in the flue gas had decreased, because the flue gas was diluted with excess air.
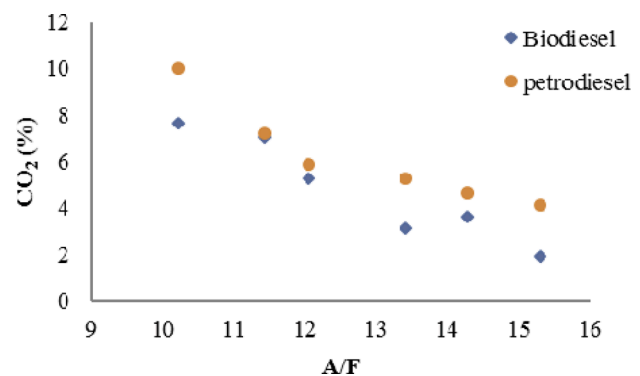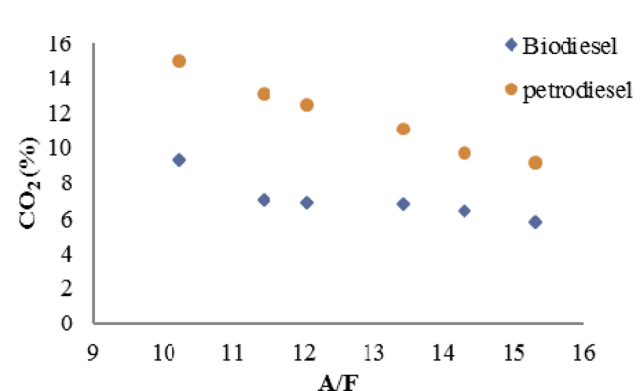

Fig. 7 – CO (ppm) vs. A/F ratio at 8 bar

Fig. 9 – CO_2 (%) VS. A/F ratio at 8 bar

Fig. 8 – CO (ppm) vs. A/F ratio at 11 bar

Fig. 10 – CO_2 (%) VS. A/F ratio at 11 bar

SO_2

Figs. 11 and 12 show variation of the emissions of sulfur dioxide (SO_2) with A/F ratios. As shown, the SO_2 emission of biodiesel is almost negligible compared to that of petrodiesel, since it contains much less sulfur than typical petrodiesel. It was expected that no SO_2 emission would be observed for biodiesel combustion. However, the small amount of sulfur may have come from the methanol content.
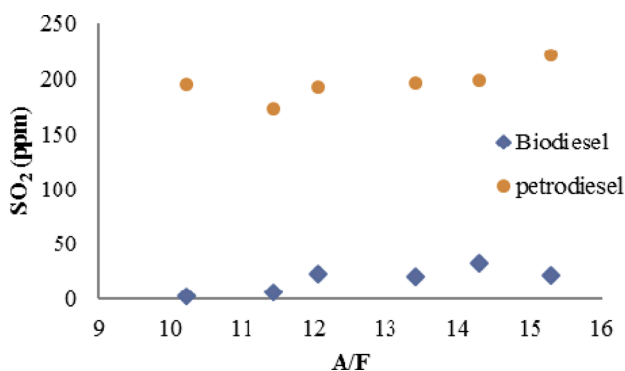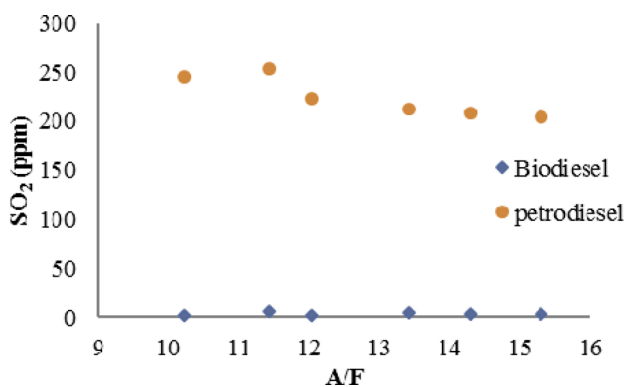

Fig. 11 – SO_2 (ppm) vs. A/F ratio at 8 bar

Fig. 12 – SO_2 (ppm) vs. A/F ratio at 11 bar

Conclusion

This experimental work compares the physical properties, emissions and combustion efficiencies of biodiesel produced from WCO and commercial petrodiesel. The combustion investigations were carried out at steady state conditions in a semi-industrial boiler, and the results were obtained after five frequent experiments, which have good repeatability.

The produced biodiesel meets ASTM standards for flash point, heating value, specific gravity, kinematic viscosity, copper corrosion, acid number, cetane number, carbon residue and total sulfur. These properties of biodiesel are also comparable with petrodiesel properties. The trends of exhaust tem-

perature and combustion efficiency of biodiesel are the same as petrodiesel at different air-to-fuel ratios. However, they are slightly lower. The CO, NO_x, SO_2 and CO_2 emissions of biodiesel are lower than those of petrodiesel at different air-to-fuel ratios and two energy levels. This work shows that biodiesel of acceptable quality and low flue gas emissions could be produced from a low-cost raw material.

Biodiesel as an alternative to petrodiesel could significantly decrease the amount of waste cooking oil. It decreases subsidies spent for agricultural over-production, as well as flue gas emissions, while lowering dependence on petrodiesel, which altogether ensures a safer environment.

Abbreviations

FFA   – Free Fatty Acid
ASTM – American Society for Testing and Materials
cSt.   – CentiStoke
ppm   – Part Per Million
N/A   – Not Available
rpm   – Revolution per Minute
WCO – Waste Cooking Oil
FA   – Fatty Acid

References

1. *Vasudevan, P. T., Briggs, M.,* J. Ind. Microbiol. Biotechnol. **35** (2008)421–430.
2. *Dincer, I.,* Renewable Sustainable Energy Rev. **4** (2000) 157–175.
3. *Demirbas, A.,* Prog. Energy Combust. Sci. **31** (2005) 466–487.
4. *Launhardt T., Thoma H.,* Chemosphere **40** (2000) 1149–1157.
5. *Alcantara, R., Amores, J., Canoira, L., Fidalgo, E., Franco, M. J., Navarro, A.,* Biomass Bioenergy **18** (2000) 515–527.
6. *Canakci, M., Gerpen, J. V.,* Trans. ASAE **44** (6) (2001) 1429–1436.
7. *Zhang, Y., Dubé, M. A., McLean, D. D., Kates, M.,* Bioresour. Technol. **89** (2003) 1–16.
8. *Canakci, M., Gerpen, J. V.,* Trans. ASAE **46** (4) (2003) 945–954.
9. *Özbay, N., Oktar, N., Tapan, N. A.,* Fuel **87** (2008) 1789–1798.
10. *Zheng, S., Kates, M., Dubé, M. A., McLean, D. D.,* Biomass Bioenergy **30** (2006) 267–272.
11. *Wang, Y., Ou, S. Y., Liu, P. Z., Xue, F., Tang, S.,* J. Mol. Catal. A: Chem. **252** (2006) 107–112.
12. *Issariyakul T., Kulkarni, M. G., Dalai, A. K., Bakhshi, N. N.,* Fuel Process.Technol. **88** (2007) 429–436.
13. *Chen, G., Ying, M., Li, W. Z.,* Appl. Biochem. Biotechnol. (2006) 129–132, 911–921.
14. *Silva, V. M. T. M., Rodrigues, A. E.,* Chem. Eng. Sci. **61** (2006) 316–331.
15. *Ngo, H. L., Zafiropoulos, N. A., Foglia, T. A., Samulski, E. T., Lin, W. B.,* Energy Fuel **22** (2008) 626–634.
16. Cao, P. G., Dubé, M. A., Tremblay, A. Y., Biomass Bioenergy **32** (2008) 1028–1036.

17. *Haas, M. J., Bloomer, S., Scott, K.,* J. Am. Oil Chem. Soc. **77** (4) (2000) 373.

18. *Jin, B., Zhu, M., Fan, P., Yu, L. J.,* Fuel Process. Technol. **89** (2008) 77.

19. *Wang, Z. M., Lee, J. S., Park, J. Y., Wu, C. Z., Yuan, Z. H.,* Kor. J. Chem. Eng. **24** (6) (2007) 1027.

20. *Usta, N., Öztürk, E., Can, Ö., Conkur, E. S., Nas, S., Çon, A. H., Can, A. Ç., Topcu, M.,* Energy Convers. Manage. **46** (2005), 741.

21. *Keskin, A., Gürü, M., Altiparmak, D., Aydin, K.,* Renewable Energy **33** (2008) 553.

22. *Haas, M. J., McAloon, A. J., Yee, W. C., Foglia, T. A.,* Bioresour. Technol. **97** (2006) 671.

23. *Zhang, Y., Dubé, M. A., McLean, D. D., Kates, M.,* Bioresour. Technol. **90** (2003) 229.

24. *Cvengroš, J., Cvengrošová, Z.,* Biomass Bioenergy **27** (2004) 173.

25. *Dorado, M. P., Ballesteros, E., de Almeida, J. A., Schellert, C., Löhrlein, H. P., Krause, R.,* Trans. ASAE **45** (3) (2002) 525.

26. *Demirbas, A.,* Energy Convers. Manage. **49** (2008) 125.

27. *Tomasevic, A. V., Siler Marinkovic, S. S.,* Fuel Process. Technol. **81** (1) (2003) 1.

28. *Wright, H. J., Segur, J. B., Clark, H. V., Coburn, S. K., Langdon, E. E., DuPuis, E. N.,* Oil & Soap (1944) 145.

29. *Freedman, B., Butterfield, R. O., Pryde, E. H.,* J. Am. Oil Chem. Soc. **63** (1986) 1375.

30. *Mansourpoor, M, Shariati, A.,* J. Chem. Eng. Process Technol. **3** (2012) 141.

31. *Leung, D. Y. C., Guo, Y.,* Fuel Process Technol. **87** (2006) 883.

32. *Barnwal, BK, Sharma, M. P.,* Renewable Sustainable Energy Rev. **9** (2005) 363.

33. *Houri Jafari, H., Baratimalayeri, A.,* Energy Policy **36** (2008) 2536.

34. *Gui, M. M., Lee, K. T., Bhatia, S.,* Energy **43** (2008) 1643.

35. *Maa, F., Hanna, M. A.,* Bioresour. Technol. **70** (1999) 1.

36. *Kansedo, J., Lee, K. T., Bhatia, S.,* Fuel **88** (2009) 1148.

37. *Keera, S. T., El Sabagh, S. M., Taman, A. R.,* Fuel **90** (2011) 42.

38. *Yo-ping Greg Wu, Ya-fen Lin, Chang-Tang Chang,* Fuel **86** (17) (2007) 2810.

39. *Tashtoush G., Al-Widyan M., Al-Shyoukh M.,* Appl. Therm. Eng. **23** (2003) 285.

40. *Batey, J.,* Combustion testing of a bio-diesel fuel oil blend in residential oil burning equipment. Tech Rep Energy Research Center, prepared for: Massachusetts Oil heat Council & National Oil heat Research Alliance; (July 2003).

41. *Heywood, J. B.,* Internal combustion engine fundamentals, McGraw-Hill; (1988).

42. *Walker, K. C.,* Royal Agricultural Society of England, **155** (1994) 43.

43. *Szybist, J., Kirby, S., Boehman, A.,* Energy Fuels **19** (2005) 1484.

44. *McCormick, R. L., Graboski, M. S., Alleman, T. L., Herring, A. M.,* Environ. Sci. Technol. **35** (2001) 1742.

45. *Cheng, A. S., Upatnieks, A., Mueller, C. J.,* Investigation of the impact of biodiesel fueling on NO_x emissions using an optical di diesel engine. SAE 2006: Powertrain & fluid systems conference, Toronto, Canada; (October 2006).

46. *Hess, K. C., Haas, M. J., Foglia, T. A., Marmer, W. N.,* Energy Fuels **19** (2005) 1749.

47. *Krishna, C. R., Celebi, Y., Wei, G., Butcher, T., McDonald, R.,* Lab tests of biodiesel blends in residential heating equipment. In: Proceedings of the 2001 national oil heat research alliance technology conference; (2001).

48. *Krishna, C. R., Butcher, T., McDonald, R., Celebi, Y., Wei, G.,* Update on use of biodiesel blends in boilers. In: Proceedings of the 2002 national oil heat research alliance technology conference; (2002).

49. *Krishna, C. R.,* Low cost bio heating oil application. Brookhaven national laboratory informal report BNL-71444–2003-IR; (2003).

50. *Krishna, C. R.,* Biodiesel blends in space heating equipment. National renewable energy laboratory report NREL/SR-510–33579; (2004)

51. *Kait, Ng H., Gan, S.,* Appl. Therm. Eng. **30** (2010) 2476.

52. *Win Lee, S., Herage, T., Young, B.,* Fuel **83** (2004) 1607.

53. *Vanlaningham, N., Gibson, H., Kaufman, B.,* Evaluation of soybean heating oil blends for use 305 in residential applications, no. 046082, ASAE paper, annual meeting held on August 23–24; 2004.

54. *Bazooyar, B., Ghorbani, A., Shariati, A.,* Fuel **90** (2011) 3078.

55. U. S. Department of Energy, Biodiesel Handling and Use Guide. National Renewable Energy Laboratory, (2008), Fourth Edition NREL/TP-540–43672.

56. *Ghorbani, A., Bazooyar, B., Shariati, A., Jokar, S. M., Ajami, H., Naderi, A.,* Appl. Energy **88** (2011) 4725.

57. *Goering, C., Schrock, M., Kaufman, K., Hanna, M., Harris, F., Marley, S.,* Evaluation of vegetable oil fuels in engines. ASAE Paper no. 871586; 1987.

58. *Vera, C. R., D'Ippolito, S. A., Pieck, C. L., Parera, J. M.,* Production of biodiesel by a two-step supercritical reaction process with adsorption refining, 2nd Mercosur Congress on Chemical Engineering, 4th Mercosur Congress on Process Systems Engineering, Rio de Janeiro 2007.