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Combustion experimental study of used motor oil and Diesel oil in circulating fluidized bed

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Abstract

Millions of tons of used automotive motor oil are disposed every year causing a severe pollution to the environment. However, the combustion of used motor oil could be a remedy to this problem. This paper investigates the combustion of used motor oil and Diesel oil in a circulating fluidized bed (CFB) combustor. Moreover, the influence of excess air ratio on temperatures and heat flux along the combustion chamber height and the concentrations of CO, NO_x, SO_2 and unburned hydrocarbons in the flue gas was studied. Furthermore, a comparison between the CFB combustion of used motor oil and that of Diesel oil was carried out. The results showed that used motor oil can be directly and efficiently burned in CFB without any treatment or purification processes. The combustion efficiency of used motor oil in CFB was about 98% for an excess air ratio of 10%. In addition, the study proved that used motor oil can be utilized as an alternative fuel in CFB combustion systems especially there was a good agreement between the combustion behaviors of used motor oil and Diesel oil in terms of temperature, heat flux and gas emissions.

Keywords: Circulating Fluidized Bed (CFB); used motor oil; diesel oil; emissions; combustion efficiency; TGA; DTA.

1. Introduction

Motor oil, which is used for lubrication purpose in the motors of cars and trucks, has to be changed on a regular basis to maintain a proper operation of the vehicle. Due to the rapid development of automotive industry and the increase in living standard, the worldwide demand for motor oil has increased to about 40 million tons/year [1]. Usually, only 40% of used motor oil is recycled while the other 60% (24 million tons/year) is disposed, which forms one of the most abundant pollutant materials [2]. Studies of the effects of disposing used oil on the environment showed that used motor oil is a very dangerous polluting product [3]. Used motor oil is considered a serious environmental problem [3]; it contains polynuclear aromatic hydrocarbons such as benzo[a]pyrene that is well known as carcinogens and high levels of heavy metals that are highly toxic.

Recycling used motor oil by using various solvent was explored [4]. A novel blend of activated alumina adsorbent and solvent extraction was utilized to refine waste lubricating oil. The results showed reasonable physical properties of the recycled lubricating oil. On the other hand, recycling used motor oil requires high operational and capital cost and still produces large quantity of pollutants [5].

Nevertheless, the controlled combustion of used motor oil can contribute in resolving its disposal problem and utilizing it as an alternative fuel. For example, utilization of waste lubrication oil into chemical feedstock or fuel oil over supported iron oxide catalysts was investigated as an alternative

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to incineration [6]. The Advantages and drawbacks of composite fuels made from industrial wastes and different ranks of coal were explored [7]. It was found that utilizing industrial wastes such as coal-water slurries containing petrochemicals as a fuel in thermal power plants was efficient in terms of both cost and energy and environmentally friendly.

An experimental investigation of the effects of the Diesel-like fuel, which was obtained from waste lubrication oil, on the engine performance and exhaust emission was carried out by Arpa et al. [8]. It was found that characteristics and distillation temperatures of the Diesel-like fuel were close to those of a typical Diesel fuel sample and the Diesel-like fuel can be used in Diesel engines without negatively affecting the engine performance. Moreover, the Diesel-like fuel increased torque, brake mean effective pressure, brake thermal efficiency while decreased brake specific fuel consumption of the engine on a full power of operation basis. Arpa et al. [9] also investigated the effects of the Gasoline-like fuel, which was also obtained from waste lubrication oil, on the engine performance and exhaust emission. The experimental results showed that the Gasoline-like fuel had a positive effect on brake power, brake thermal efficiency, mean effective pressure and specific fuel consumption. The Gasoline-like fuel raised CO and CO_2 emissions and exhaust temperature while it decreased hydrocarbon (HC) in the exhaust as compared to gasoline fuel.

On the other side, fluidized bed combustion can be used for energy production or incineration of almost any material containing carbon and hydrogen in a combustible form, whether it is in the form of solid, liquid, slurry, sludge, paste or gas [10]. Combustion of liquid fuels in fluidized beds has been recently proved a successful approach to create more homogeneous and controlled temperature distribution as well as to minimize the emissions of some pollutants such as nitrogen oxides and soot. Moreover, fluidized beds can also be used to efficiently burn liquid wastes or raw vegetable oils, even without any preparatory chemical treatment (such as oxidization and absorption), which is typically required for enhancing the atomization behavior in traditional burners. Circulating Fluidized Bed (CFB) combustion has emerged as the most preferable combustion system in steam generation technologies in recent times [11]. Circulating fluidized bed can be used for a wide range of fuel applications with low pollution emissions [12]. In addition, the combustion efficiency of CFB is higher than other combustion technologies such as bubbling fluidized beds [13]. Several studies have been reported in the literature on the utilization of circulating fluidized bed technology to combust wastes and hard fuels such as the co-firing of oil sludge with coal-water slurry [12] and combustion of olive cake [14], heavy liquid fuel (Mazut) [10], petroleum coke [15], liquid bio-fuels [16], Refuse Derived Fuel [17], etc.

The present study investigates experimentally the combustion behavior of used automotive motor oil, directly without any treatment or purification processes, in circulating fluidized bed combustor. Specifically, the influence of excess air ratio on the combustion process was studied and compared to that of Diesel oil. Temperatures and heat flux along the combustion chamber height and the concentrations of CO, NO_x, SO_2 and unburned hydrocarbons in the flue gas were measured. The combustion efficiency was estimated. In addition, a comparative study of the CFB combustion of used motor oil and Diesel oil was carried out.

2. Thermal analysis

The thermal analysis of used motor oil was studied to explore its thermal characteristics. The analysis included Thermal Gravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) as follows.

2.1. Thermal Gravimetric Analysis (TGA)

Thermal gravimetric analysis is performed to determine the changes in a sample weight according to a temperature program in a controlled atmosphere. The atmosphere is purged with an inert gas to prevent oxidation or other undesired reactions. Sample is placed in a platinum pan of a high precision balance. The pan is placed in an electric oven where the sample temperature is measured by a thermocouple. The change in weight occurs due to decomposition of some components of the sample into a gas. The temperature at which the highest weight loss takes place can be recognized from a derivative weight loss curve.

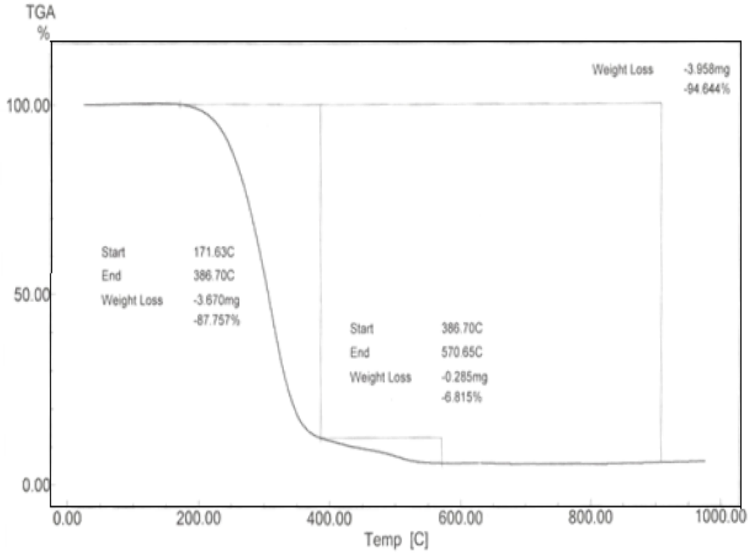
A sample of used motor oil that weights 4.182 mg was heated gradually to 1000°C with a rate of 10 ^{o}C/min. As shown in Figure 1a, the sample preserved its weight until it reached 171.63^{o}C. Then, the sample lost about 87.8% of its weight as its temperature reached 387°C. Eventually, a total weight loss of about 94.6% of the sample weight took place as the sample temperature reached 570°C.

2.2. Differential Thermal Analysis

The Differential Thermal analysis (DTA) detects the exothermic or endothermic changes in a sample relative to an inert reference such as Al_2O_3. Both the sample and the reference undergo identical thermal cycles where any temperature difference between the sample and the reference is recorded. A sample of used motor oil that weights 4.182 mg was heated gradually to 1000°C with a rate of 10 °C/min, as shown in Figure 1b. A heat release of 435 J/g was detected as the sample reached 356.31°C and a heat release of 106.11 J/g was detected as the sample reached 376.15°C.

It was concluded, from the thermal analysis of used oil, that a rapid weight loss (76%) and high heat release (435 J/g) took place through the initial heating of sample (up to about 350°C).

(a)



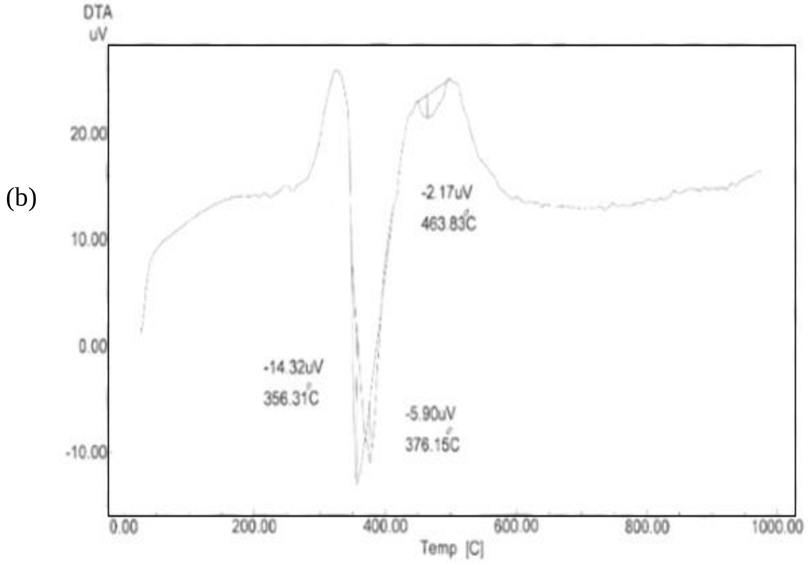


Figure 1. TGA and DTA for used motor oil. a) TGA, b) DTA.

3. Combustion Experimental Setup

The CFB test rig used in this study consists of a combustion chamber and auxiliary systems such as bed recirculation system, air supply, fuel feeding, and exhausts gas suction.

A schematic diagram of the CFB test rig is shown in Figure 2. The combustion chamber is an insulated steel cylinder with 145 mm inner diameter, 2 m height, and 12 mm wall thickness. There are two inlets to the combustion chamber, at heights of 0.3 m, 0.7 m above the distributor plate, to supply secondary air. The bed recirculation system includes connecting pass, cyclone, and return leg. The connecting pass connects the combustion chamber to the cyclone. The cyclone and the return leg complete together the cycle of the circulating sand. The circulating sand returns to the combustion chamber at 200 mm above the air distributor, through the return leg, which is inclined at 45^o. Air is used as a carrier for the returned sand to the combustion chamber with the aid of gravity. The main air supply is an air blower with 15 kW capacity and 2850 rpm. The primary air enters the distributor through a cone vessel of 100 mm bottom diameter and 140 mm top diameter. The distributor has 35 nozzles. Each nozzle is of 10 mm outer diameter and 5 mm inner diameter and has four holes of 2.5 mm diameter on the circumference. The flue gas is drawn to the chimney by a suction fan. The bed material is silica sand with a mean particle diameter of 0.543 mm, real density 2460 kg/m^3, bulk density of 1414 kg/m^3 and bed height of about 100 mm.

Initially, a gaseous fuel that commercially named Butagas is burned to warm up the combustion chamber. Butagas is a mixture of 70% butane and 30% propane by volume. It has a calorific value of 45.562 MJ/kg and a density of 2.4 kg/m^3 (at N.T.P). Butagas supply system, as shown in Figure 2, consists of four Butagas bottles, which are connected together to provide a capacity of 112 kg. Butagas is injected to the primary air pipe. The oil is fed into the bed through a main immersed pipe that splits into two pipes. Each pipe has an inner diameter of 10 mm and has four holes of 2 mm inner diameter on the pipe wall.

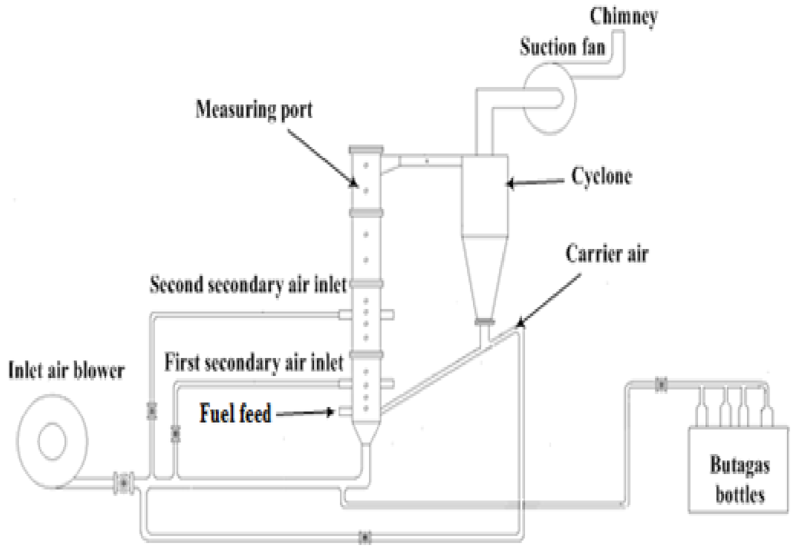


Figure 2. Schematic diagram of circulating fluidized bed.

Temperatures along the combustion chamber were measured by shielded type K thermocouples. The accuracy of thermocouple was ±2 ºC. Samples of flue gas were drawn from the cyclone exit to the electrochemical cells analyzer where the concentrations of, CO, NO_x, SO_2, HC, CO_2, and O_2 were measured. The readings of flue gases are required to be related to specific oxygen content (normalization) in order to comply with certain environmental legislations,. Therefore, the measured emissions of CO, NO_x, SO_2, and HC were recalculated based on 7% O_2 in flue gases. The accuracy of O_2 concentrations and gas emissions measurements were ±1% and ±4%, respectively.

The heat flux to the combustion chamber walls was measured by a plug-type heat flux meter, which has a plug of known thermal conductivity and dimensions. The plug has two copper constantan thermocouples that are separated by a known distance along the axis of the plug. Hence, the heat flux to the combustion chamber wall can be estimated at every measuring port in kW/m^2. The uncertainty of measured heat flux was ±5%.

The combustion efficiency, which is the ability of a combustor to burn fuel, is estimated based on CO and HC emissions as follows.

$$\eta_c = \frac{Q_{in} - Q_{CO} - Q_{HC}}{Q_{in}} \quad (1)$$

where η_c is combustion efficiency, Q_{in} is heat input, Q_{CO} is heat losses due to incomplete combustion of carbon and Q_{HC} is heat loss due to unburned hydrocarbons.

Q_{CO} is determined by

$$Q_{CO} = m_{CO} \times (C.V.)_{CO} \quad (2)$$

where m_{CO} is the mass of CO in kg per kg of fuel and $(C.V.)_{CO}$ is the calorific value of carbon monoxide (10160 kJ/kg).

Q_{HC} is determined by

$$Q_{HC} = m_{HC} \times (C.V.)_{HC} \quad (3)$$

where m_{HC} is the mass of unburned HC in kg per kg of fuel and $(C.V.)_{HC}$ is assumed as the calorific value of fuel.

Two types of fuels were combusted and compared in this study; used motor oil and Diesel oil. The properties of these fuels are listed and compared in Table 1. The Table shows a big similarity in the properties of the two oils.

Table 1. The properties of used motor oil and Diesel oil.

	Ultimate analysis in mass basis				Calorific value (kJ/kg)	Theoretical air to fuel ratio	Density kg/m^3
	Carbon (%)	Hydrogen (%)	Sulphur (%)	Nitrogen (%)			
Used motor oil	86.45	13.5	0.42	0.09	47066	14.52	828
Diesel oil	86.3	12.8	0.9	-	44162	14.27	850

3.1. Operating Conditions

The combustion process started with the aid of Butagas combustion, which was gradually decreased and stopped completely once the oil was independently combusted. The study explored the effect of excess air ratio on the combustion characteristics such as temperature, heat flux and gas emission at different operating conditions. In the combustion of used motor oil, the feed rate of 8 kg/h was examined firstly, and then decreased gradually to 4 kg/h in an attempt to achieve better combustion conditions. It was found that the used oil feed rate of 4 kg/h (thermal load of 52.3 kW) offered good combustion stability. The excess air ratio (EA) ranged from 1.1 to 1.6. On the other hand, the feed rate of the Diesel oil was steady at 8 kg/h while the excess air ratio was increased gradually from 1.1 to 1.7. The experimental parameters of combustion are listed in Table 2.

Table 2. Combustion experimental parameters of used motor oil and Diesel oil.

Fuel	Used motor oil				Diesel oil				
Fuel feed rate, kg/h	4				8				
Excess air ratio (EA)	1.1	1.3	1.5	1.6	1.1	1.3	1.5	1.6	1.7
Air flow rate kg/h	63.9	75.5	87.12	92.93	125.6	148	171.24	182.7	194
Thermal load, kW	52.3				98.14				
Thermal load*, MW/m^2	1.58				3.17				

***** Thermal load is estimated in MW per unit area of combustion chamber cross section.

4. Results and Discussion

4.1. Combustion of Used Motor Oil

Preliminary experiments were carried out with feed rates of used motor oil 8, 7 and 6 kg/h. It was observed during the experiments that using the aforementioned feed rates of used oil resulted in high levels of CO and HC emissions in the flue gas, which indicated a severe incomplete combustion. Therefore, the feed rate of used oil was reduced to 4 kg/h in order to obtain a better combustion process.

Figure 3 shows the temperature distribution and the heat flux along the combustion chamber height for a feed rate of used oil of 4 kg/h and an excess air ratio of 1.1. It is shown that the temperature increased to 1000^{o}C at the height of 0.4 m and the combustion process developed gradually along the combustion chamber. Thereafter, temperature decreases to 725^{o}C at the height of 1.8 m. The heat flux along the combustion chamber height increased gradually and reached to about 45 kW/m^2

at the height of 1.8 m. One can say that the combustion of used oil seems delayed along the fluidized bed.

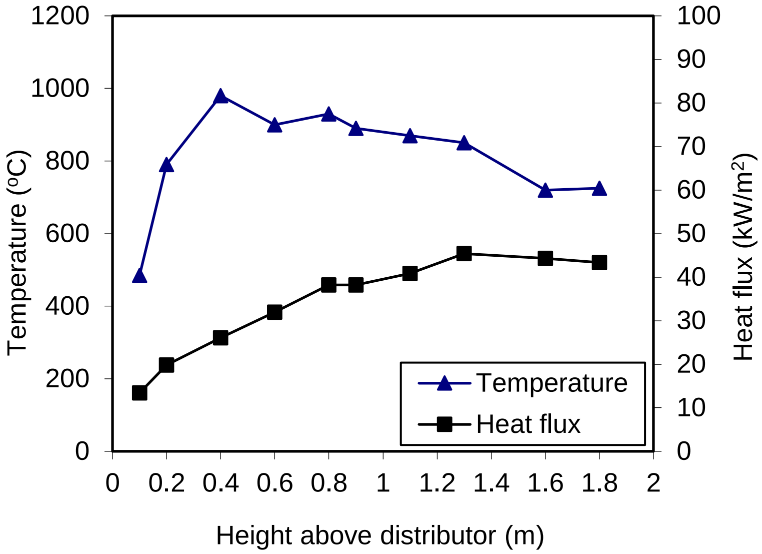


Figure 3. Temperature and heat flux distribution along the combustion chamber for used motor oil combustion (used oil feed rate = 4 kg/h).

Figure 4 illustrates the effect of excess air ratio on maximum temperature of bed. Expectedly, increasing excess air ratio results in decreasing bed temperature. Specifically, bed temperature decreased from 980°C to 620°C when excess air ratio increases from 1.1 to 1.6, respectively.

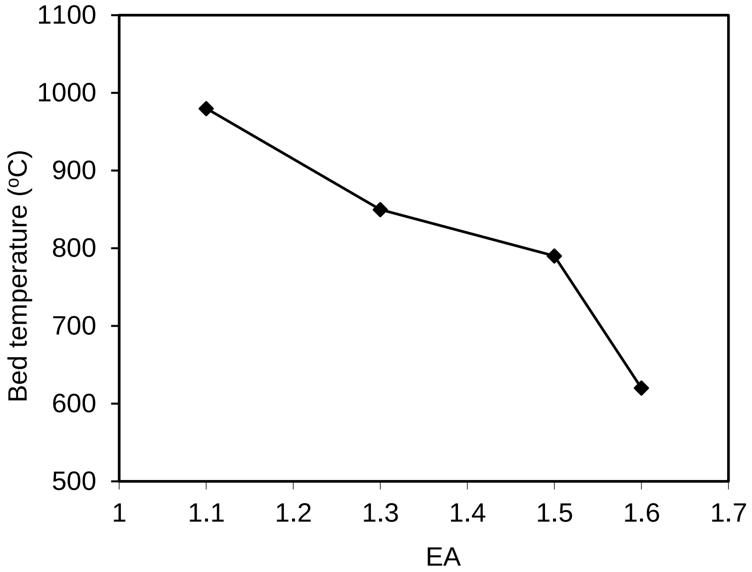


Figure 4. Effect of excess air ratio on bed temperature for used oil combustion.

The influence of excess air ratio on CO and NO_x emissions from used oil combustion are shown in Figure 5. The CO emission significantly increases from 0.1% to 1.7% with increasing the excess air ratio from 1.1 to 1.6, respectively. This can be attributed to the decrease in combustion temperature occurred by the excess air. The NO_x emissions decreased from 134 ppm to 109 ppm with increasing the excess air ratio from 1.1 to 1.6, respectively. This may be attributed to the cooling effect of excess air that decreased the combustion temperature. Consequently, the thermal NO_x emission that resulted from the oxidization of the air's nitrogen decreased. In addition, the low nitrogen content of used oil also reduces the resulted NO_x emission. On the other side, NO_x emissions have a reverse relationship with CO emissions where CO reduces NO to elemental nitrogen according to the following mechanism [18].

$$2\,CO + 2\,NO \rightarrow 2\,CO_2 + N_2 \tag{4}$$

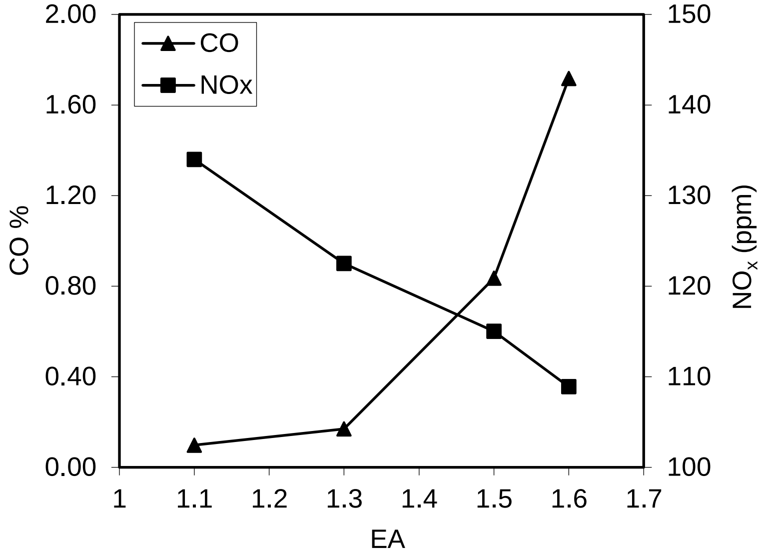


Figure 5. Effect of excess air ratio on CO and NOx emissions for used oil combustion.

The effect of excess air ratio on SO_2 and unburned hydrocarbon emissions from used motor oil combustion is illustrated in Figure 6. The SO_2 emission ranged between 166 ppm and 257 ppm. This can be attributed to the low Sulphur content of used motor oil. The Figure also shows that the emission of unburned hydrocarbons ranged between 0.13% and 0.31%.

The effect of excess air ratio on the combustion efficiency of used oil is illustrated in Figure 7. The very small amounts of excess air do not lead to good mixing and complete combustion. On the other side, the large amounts of excess air include more nitrogen content (inert gas) which decrease the combustion temperature and impede the good mixing of fuel and oxygen. This leads to increase the emissions of unburned HC. The experiments show that the maximum efficiency occurred at EA=1.3. Anyway, it is obvious that the present range of excess air ratio has not a significant effect on the combustion efficiency. An average combustion efficiency of about 98% was estimated for the combustion of used oil with excess air ratios range from 1.1 to 1.6. However, the influence of the excess air ratio on the combustion efficiency of used oil was as small as ±1%.

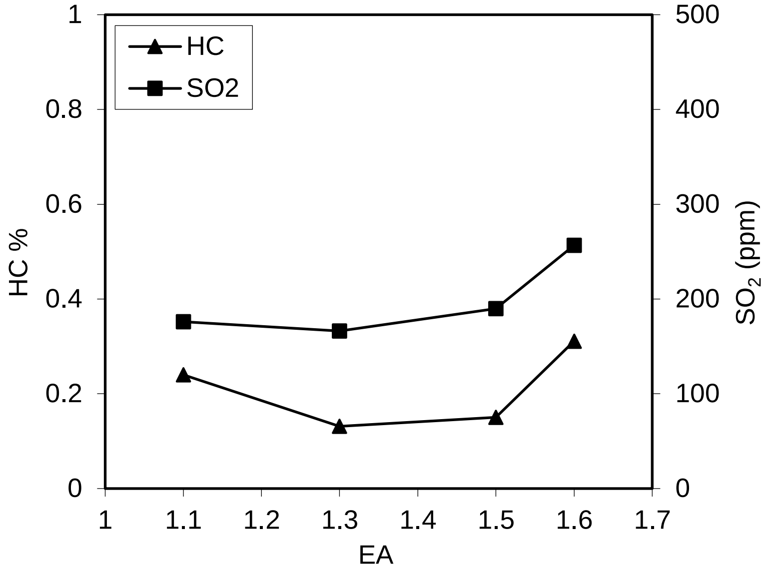


Figure 6. Effect of excess air ratio on HC and SO_2 emissions for used oil combustion.

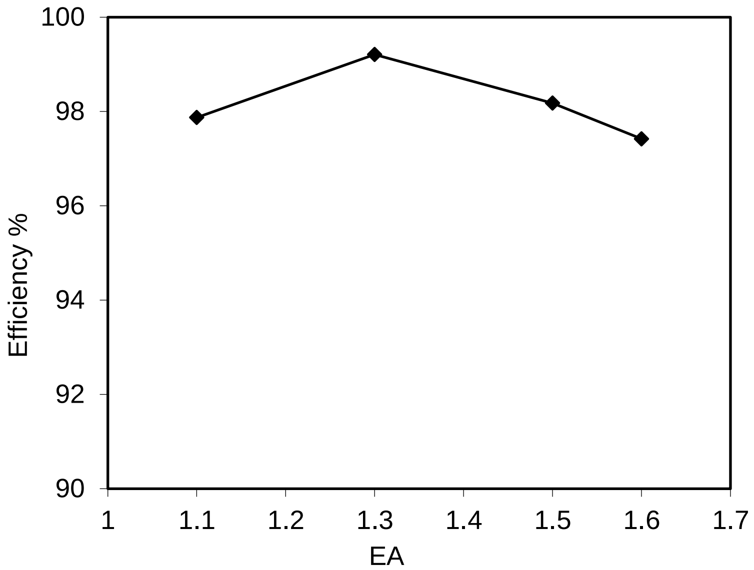


Figure 7. Effect of excess air ratio on combustion efficiency for used oil combustion.

4.2. Combustion of Diesel Oil

The temperature distribution and heat flux along the combustion chamber height for the combustion of Diesel oil with an excess air ratio of 1.1 is illustrated in Figure 8. It is notable that the temperature was the highest at bed region (about 1100^{o}C), which indicates the majority of combustion process occurred at the lower region of the combustion chamber. Temperatures then decreased along the combustion chamber height to about 800^{o}C due to heat loss through the walls of the combustion chamber. The Figure also shows that the heat flux, produced by the combustion of Diesel oil, decreased from 100 to 50 kW/m^2 gradually along the height of the combustion chamber. The Diesel oil seems to burn immediately after injection.

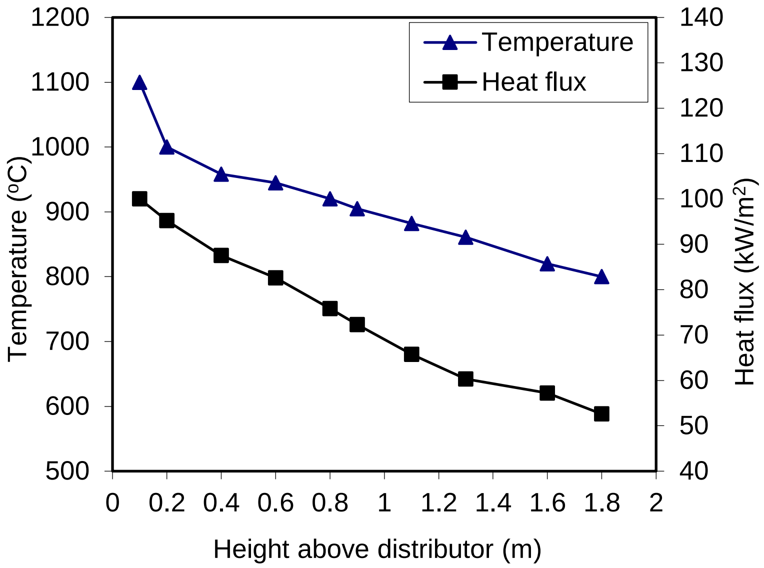


Figure 8. Temperature and heat flux distributions along the combustion chamber for Diesel oil combustion.

Figure 9 illustrates the effect of excess air ratio on maximum temperature of bed. This temperature was always at a height of 0.1 m above the air distributor. It was observed that increasing excess air ratio from 1.1 to 1.7 resulted in decreasing bed temperature from 1100°C to 1000°C. This is attributed to the cooling effect of excess air.

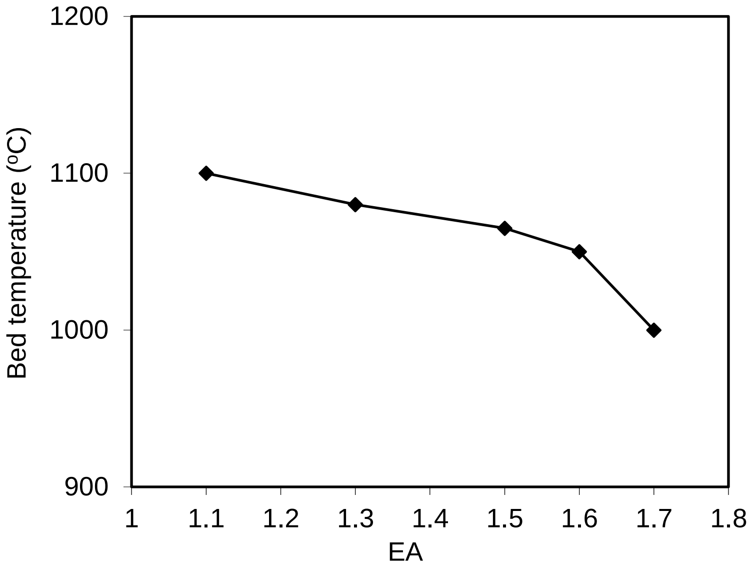


Figure 9. Effect of excess air ratio on bed temperature for Diesel oil combustion.

The influence of excess air ratio on CO and NO_x emissions from Diesel oil combustion is shown in Figure 10. The CO emission slowly increased from 0.63% to 0.68% with increasing the excess air from 1.1 to 1.7 due to the decrease in combustion temperature occurred by the excess air. Contradictorily, NO_x emissions decreased from 20 ppm to 4 ppm with increasing the excess air ratio from 1.1 to 1.7 due to the cooling effect of excess air that decreased the combustion temperature besides the reverse relationship between CO and NO_x emissions, which was previously referred to in equation (4).

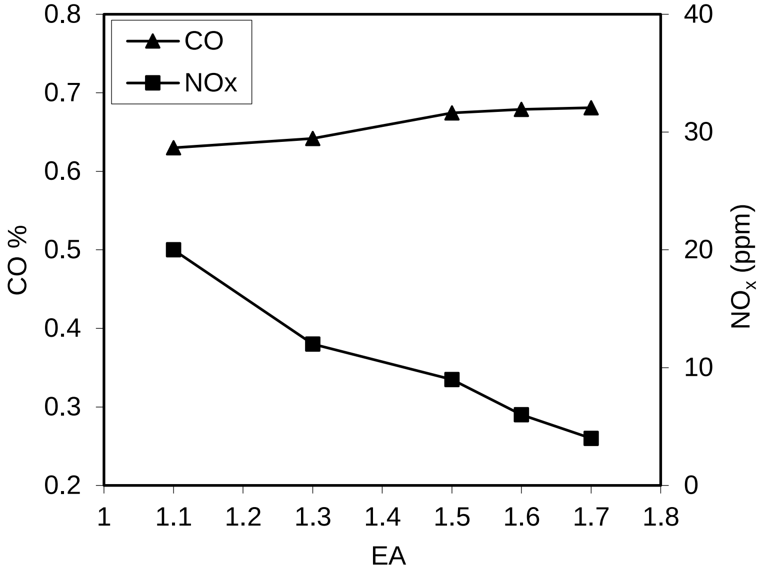


Figure 10. Effect of excess air ratio on CO and NOx emissions for Diesel oil combustion.

The SO_2 and HC emissions from Diesel oil combustion are shown in Figure 11. It is notable that increasing the excess air ratio up to 1.3 decreases the unburned HC to almost zero then increasing the excess air ratio more than 1.3 increases the unburned HC. The emission of unburned hydrocarbon ranged between 0% and 0.38%. Also, the SO_2 emission decreased from 1300 ppm to 995 ppm with increasing the excess air ratio from 1.1 to 1.7. The high values of SO_2 emission are attributed to the high Sulphur content of Diesel oil (0.9%).

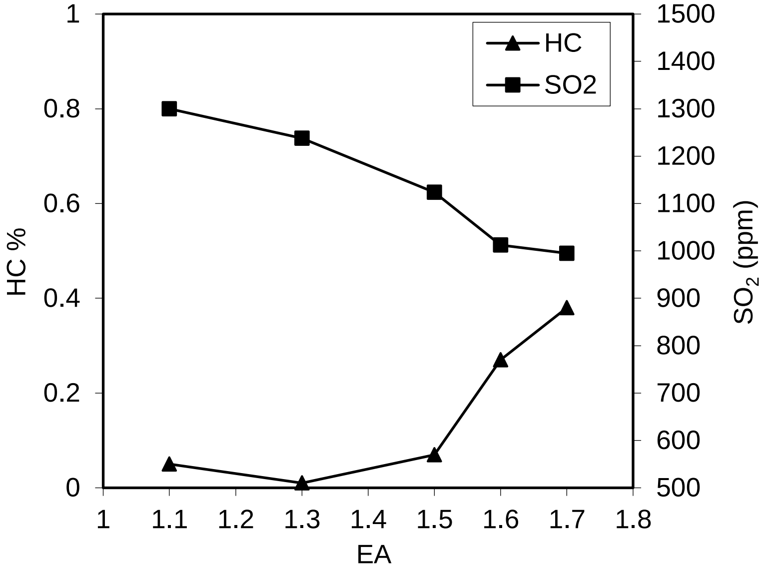


Figure 11. Effect of excess air ratio on HC and SO_2 emission for Diesel oil combustion.

Figure 12 shows the effect of excess air ratio on the combustion efficiency of Diesel oil. It is clear that increasing the excess air ratio from 1.1 to 1.5 did not have a significant effect on the combustion efficiency. However, increasing the excess air ratio from 1.5 to 1.7 decreased the combustion efficiency from 94% to 85%.

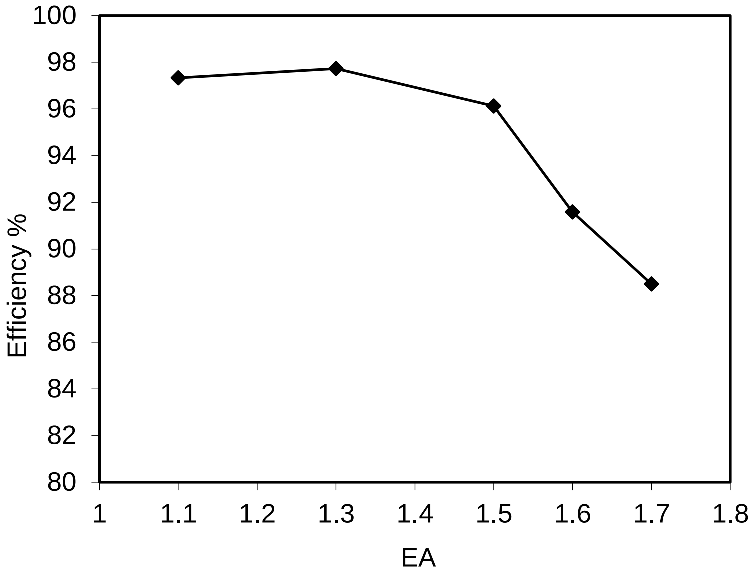


Figure 12. Effect of excess air ratio on combustion efficiency of Diesel oil.

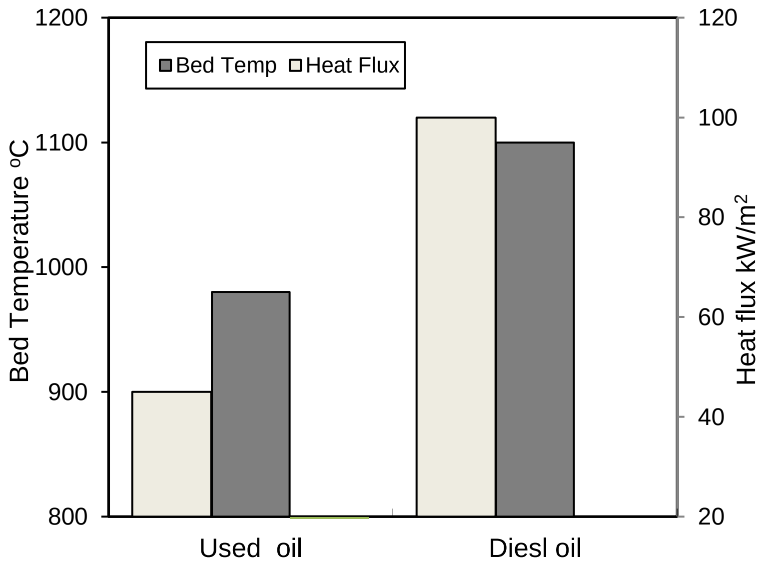


Figure 13. Bed temperatures and heat fluxes for combustion of used motor oil and Diesel oil.

4.3. Comparison Between the Combustion of Used Motor Oil and Diesel Oil

Figure 13 shows the comparison between bed temperature and heat flux of the combustion of used motor oil and Diesel oil. It can be noticed that the bed temperature and heat flux of used motor oil combustion are lower than those of Diesel oil combustion. In addition, the visual experimental observations showed that the flame of the used oil combustion was more luminous than that of the Diesel oil combustion. This may be attributed to the particular composition of used motor oil.

The comparison between CO and NO_x emissions of the combustion of used motor oil and Diesel oil are shown in Figure 14. It is notable that CO emission of used oil combustion is lower than that of Diesel oil combustion. Oppositely, the NO_x emission of used oil combustion is remarkably higher than that of Diesel oil combustion due to the high nitrogen content of used oil as compared to Diesel oil.

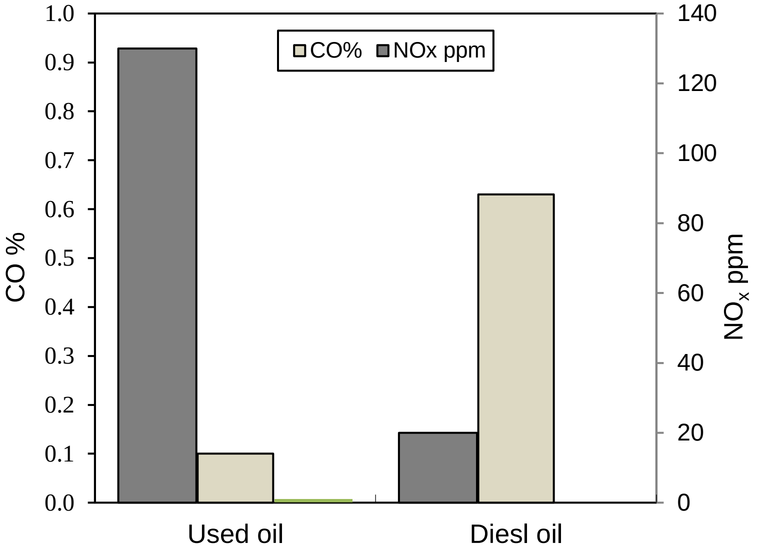


Figure 14. CO and NOx emissions for combustion of used motor oil and Diesel oil.

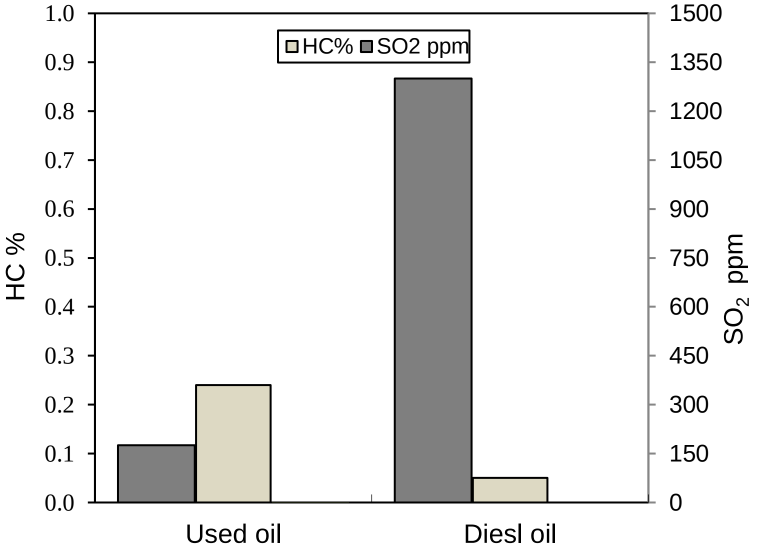


Figure 15. HC and SO_2 emissions for combustion of used motor oil and Diesel oil.

Figure 15 shows the comparison between unburned hydrocarbon and SO_2 emissions of the combustion of used motor oil and Diesel oil. It is shown that SO_2 emission of Diesel oil combustion is greater than that of used oil combustion. This is due to the higher sulphur content of Diesel oil.

Contradictorily, the unburned hydrocarbon resulted from used motor oil combustion is higher than that of Diesel oil combustion.

Lastly, Figure 16 illustrates that the combustion efficiency of used motor oil is a bit higher than that of Diesel oil.

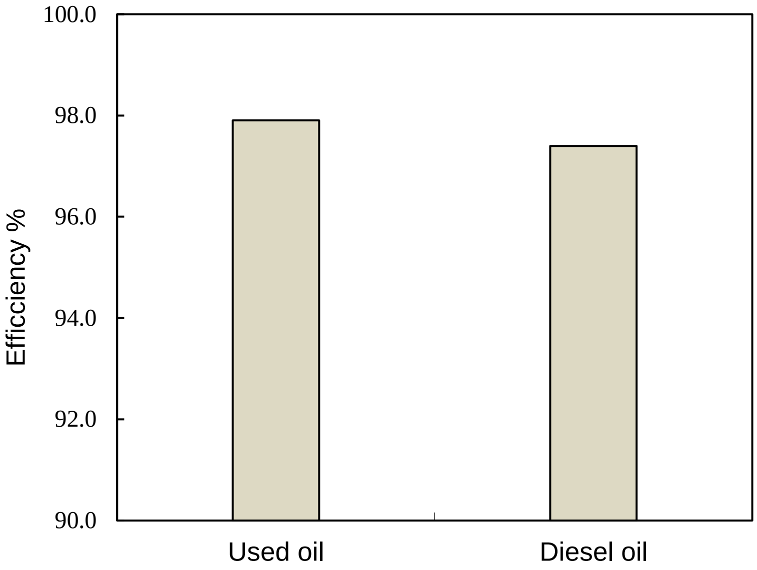


Figure 16. Combustion efficiency of used motor oil and Diesel oil.

5. Conclusions

The circulating fluidized bed combustion of used motor oil was experimentally investigated and compared to that of Diesel oil. The study proved that used motor oil can be directly and efficiently burned in CFB without any treatment or purification processes. This is considered a promising approach to get rid of the millions of tons of used oil yielded every year and an effective remedy to the severe environmental problem caused by disposing used motor oil. On the other side, used motor oil can be utilized as an alternative fuel in combustion systems especially many of the chemical properties of used motor oil are remarkably close in their values to those of Diesel oil. Hence, there was a good agreement between the combustion behaviors of the two oils in terms of temperature, heat flux and gas emissions. In addition, the CFB of both oils do not need high levels of excess air; only a percentage of 10% is sufficient. Furthermore, the combustion efficiency for both oils was higher than 97%.

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