Jurnal
Teknologi

Full Paper

COMBUSTION CHARACTERISTICS OF RICE BRAN OIL BIODIESEL IN AN OIL BURNER

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Article history
Received
10 September 2017
Received in revised form
14 November 2017
Accepted
15 January 2018
Published online
1 April 2018

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Graphical abstract

Abstract

The concept of biodiesel as an alternative fuel is not an overnight thought, but the escalating prices, pungent emission gases and non-ecological behavior of fossil fuels has constrained the researchers to take the necessary steps. Biodiesels which are renewable in nature and having environmental friendly attribute have shown the potential to be the perfect replacement for the diesel fuels. Similarly, this study demonstrates the characteristics of Rice Bran Oil (RBO) which can be used as a latent substitute for diesel products. RBO is a vegetable oil, which is extracted from the rice bran (by-product of rice grain). Since rice is the staple diet for more than half of the world population, the quantity of RBO that can be extracted is enormous. In this study, the converted RBO into biodiesel (RBOBD) was blended with diesel to produce B5, B15 and B25 to determine physical properties and combustion performance. Owing to highly packed molecules of RBOBD, the properties such as density, kinematic viscosity and surface tension are higher in RBOBD and its blends than diesel. In contrast, the calorific value is lower. In the combustion test, the highest wall temperature is achieved at stoichiometric fuel mixture, while among the fuels, the wall temperature decreases as the biodiesel proportion increases in the blends. Moreover, in B25, emissions such as CO and SO_2 are 68% and 50% lower than that of diesel respectively. However, due to the additional oxygen present in the biodiesel structure, NO_x emission of B25 is 15.67% higher than diesel.

Keywords: Rice Bran Oil Biodiesel, combustion characteristics, equivalence ratio, gaseous emission, biodiesel blends

Abstrak

Konsep biodiesel sebagai bahan api alternatif bukanlah baru sahaja difikirkan, namun harga minyak yang semakin meningkat, pelepasan gas emisi yang sentiasa meningkat, dan tingkah-laku bukan ekologi bahan api fosil telah menghalang penyelidik untuk mengambil langkah-langkah yang diperlukan. Biodiesel yang boleh diperbaharui dan mempunyai sifat mesra alam sekitar telah menunjukkan potensi untuk menjadi pengganti yang sesuai untuk bahan api diesel. Begitu juga, kajian ini menunjukkan ciri-ciri bahawa Rice Bran Oil (RBO) boleh digunakan sebagai pengganti pendam untuk produk diesel. RBO merupakan minyak sayuran, yang diekstrak daripada bran padi (hasil sampingan bijirin padi). Oleh kerana beras merupakan makanan ruji untuk lebih daripada separuh penduduk dunia, kuantiti RBO yang boleh diekstrak adalah amat besar. Dalam kajian ini, RBO yang ditukarkan kepada biodiesel (RBOBD) telah diadun dengan diesel untuk menghasilkan B5, B15 dan B25 bagi menentukan sifat fizikal dan prestasi pembakaran. Disebabkan molekul RBOBD yang sangat padat, sifat seperti ketumpatan, kelikatan kinematik dan ketegangan permukaan adalah lebih tinggi untuk RBOBD dan adunannya berbanding diesel. Sebaliknya, nilai kalori adalah lebih rendah. Dalam ujian pembakaran, suhu dinding tertinggi dicapai pada campuran bahan api stoikiometri; sebaliknya perbandingan antara jenis bahan api, suhu dinding berkurangan apabila kadar biodiesel meningkat dalam campuran bahanapi. Selain itu, bagi adunan B25, kepekatan emisi seperti CO dan SO_2 adalah 68% dan 50% lebih rendah daripada diesel, masing-masing. Walau bagaimanapun, disebabkan terdapat oksigen tambahan dalam bahanapi biodiesel, emisi NOx untuk B25 adalah 15.67% lebih tinggi berbanding diesel.

Kata kunci: Biodiesel minyak bran padi, ciri pembakaran, nisbah kesetaraan, emisi bergas, adunan biodiesel

1.0 INTRODUCTION

Fossil fuels have been the most economical and beneficial fuels over the decades [1]. From industrial operation to home-stoves ignition, from airplane operations to automobile applications, fossil fuels were always preferred due to their availability, low prices and combustion properties [2]. However, due to such an overwhelming demand and consumption, the fossil fuel reservoirs are diminishing and prices are increasing day by day. As per estimation by International Energy Agency, the global energy consumption will rise to 53% by 2030 [3-4]. The problem with fossil fuels is not only associated with their short-lived reservoirs but the exhaust emissions of such fuels are also found to be fatal for environment and human lives [2]. From these emissions, nitrogen oxides (NO_x), carbon monoxide (CO), sulphur dioxide (SO_2) and unburnt hydrocarbons (UHC) are found in abundant quantity [5]. NO_x is the generalized term given to the compounds of oxygen and nitrogen e.g. NO, NO_2 and N_2O [6-7]. NO_x emissions are the most powerful emissions that can damage the environment in the form of acid rain, greenhouse effect and human diseases. When NO_x and SO_2 combine with water vapors, they produced H_2SO_4 and HNO_3, which are the main precursors for acid rain. Meanwhile NO_x and CO are the main pollutants in the formation of tropospheric ozone, which is greenhouse gas [4], [8].

Considering such atmospheric and depletion concerns, the environmentalists are forced to find an energy source which not eco-friendly but also renewable [9-10]. Biodiesel as an alternative fuel was first experimented in 1900 by the inventor of diesel engine, Rudolph Diesel, who tested peanut oil directly in diesel engine. Although, due to higher viscosity, the diesel engine could not start. The problem was then solved using different methods including pyrolysis, dilution with solvents, thermal cracking, micro-emulsions and transesterification. From these methods, transesterification was preferred due to the presence of catalyst. Transesterification is a process in which triglyceride and alcohol are reacted in the presence of catalyst to produce methyl ester and glycerol. Usually, methanol is used as alcohol in transesterification process, thus, the process is also called Methenolysis [11]. Figure 1 shows the transesterification process.

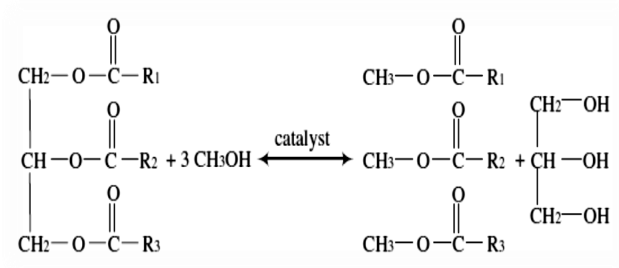

Figure 1 Reaction of triglyceride with methanol to produce methyl ester and glycerol

Biodiesel's properties i.e. kinematic viscosity, density and calorific value, do not resemble with diesel even after transesterification process. Hence, biodiesel is preferred to be blended with diesel at different proportions [12]. Biodiesel blends are categorized in the form of "BXX" where "B" stands for biodiesel and "XX" shows its blend percentages e.g. "B50" indicates 50% of biodiesel is blended with 50% of diesel. Biodiesel is a petroleum based fuel which is produced from animal fat or vegetable oil i.e. palm oil, coconut oil etc. [13-14]. Similarly, Rice Bran Oil (RBO) is also a vegetable oil which is extracted from Rice Bran (a by-product of Rice grain while milling for polished rice) [15].

RBO is extracted from rice bran via solvent extraction process. Solvent extraction is a process in which solvent and water are used to separate different compounds based on their solubility. In commercial extraction processes, the widely-used solvents are hexane and SL-MI (mixture of alcohol and acetone) [16]. Under the regulations of FDA (Food and Drug Administration) hexane is quite safe for the purposes of solvent [17].

The process starts with preheating solvent extraction at 50°C for half an hour. Then, stabilized rice bran is added into the extractor keeping the rice bran and solvent ratio to 5:1 (w/v). The process is carried out for approximately half an hour. Then filtration is done to separate residual bran. For solvent recovery, the mixture i.e. rice bran and solvent is shifted to batch distillation column where Rice Bran Oil is collected at the bottom of column [16]. RBO as a cooking oil, is known as "Heart Oil" in Japan, because it helps in reduction of cholesterol in body which ultimately reduces the risk of heart attack [18].

Research regarding Rice Bran Oil Biodiesel (RBOBD) is the main topic of interest in Oil Technology nowadays. Many researchers have used RBOBD and its blending in different applications e.g. diesel engine, agricultural diesel engine and variable compression engine to compare the physical, performance and emission characteristics with diesel. Senthil Kumar and Manimaran [19], by means of experiments showed that as the proportion of RBOBD increases in diesel, the kinematic viscosity increases abruptly, thus, viscosity of B100 was found to be 6 times higher than Conventional Diesel Fuel (CDF). The similar behavior was also witnessed for density by Ahmed *et al*. [20]. It was found that RBOBD blends possessed higher density that diesel. Consequently, the density of B100 was 7.6% higher than CDF.

Moreover, Dhurva and Math [21] investigated that with increasing the percentage of RBOBD in diesel, specific gravity increases gradually. Among the RBOBD blends, B100 showed highest specific gravity i.e. 0.875, which was 8% higher than diesel's specific gravity i.e. 0.81. Although, the trend was almost opposite in calorific values. Biodiesel blends possessed lower calorific value than diesel. On the other hand, the emission characteristics of RBOBD were also examined by different researchers. Pinkesh [22] compared the emissions of RBOBD blends and diesel in agricultural diesel engine and detected that RBOBD blends produce less CO than CDF.

The emissions were measured at different loads. At low loading condition, CO emission was quite low for all fuels, but once the load crossed 50%, CO emission increased rapidly. Among the fuels, B100 produced 30% less CO than diesel. NO_x emission was also inspected by Pinkesh. Biodiesel's chemical structure possesses additional oxygen. Thus, as the amount of RBOBD increases in diesel, NO_x emission increases. Hence B100 produces 30% higher NO_x than diesel.

Biodiesel blends and diesel were also experimented in variation compression ratio diesel engine by Vasudeva *et al*. [23]. By means of experiments it was discovered that RBOBD blends produce lower CO. Malipatil and Bandi [24] tested BROBD blends i.e. B20, B40, B60, B80 and diesel in diesel engine and assessed that exhaust gas temperature (EGT) increases as the concentration of RBOBD increases in diesel.

2.0 METHODOLOGY

RBOBD and RBOBD blends were prepared at the Combustion Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia. RBOBD, like any other biodiesel, was produced via transesterification process. Transesterification process (aka. Alcoholysis) is a process of breaking down fat/oil by alcohol to produce ester-based biodiesel and glycerol [25]. Biodiesel production follows three steps i.e. pre-treatment, transesterification and post-treatment [26]. In pre-treatment step, the crude RBO was heated at 60°C, 400 rpm for 1 hour in a rotary evaporator to remove moisture and impurities. In transesterification step, 25% of methanol (v/v to crude RBO) and 1% of KOH (w/w to crude RBO) were mixed with crude RBO and the mixture was reacted for 2 hours, at 60°C and 400 rpm. Then, the mixture was poured into a separation funnel. After few hours (preferably 12 hours), the mixture was clearly separated into two distinct layers i.e. upper layer as methyl ester and lower layer as glycerol. In post-treatment step, the glycerol was drained from the bottom tap of separation funnel while methyl ester was washed with distilled water to remove residual glycerol. The temperature and quantity of distilled water were 50°C and (50% w/w to crude RBO) respectively. After several washings, the Rice Bran Oil Methyl Ester (RBOME) was dried at 50°C, 400 rpm for half an hour to remove water particles. After drying RBOME, it was further filtered with filter paper to remove any wax or soap, thus, the pure RBOME was obtained.

2.1 RBOBD Blends and Physical Properties

RBOBD was blended with diesel to obtain B5, B15 and B25. The physical properties i.e. density at 15°C, kinematic viscosity at 40°C, surface tension at 15°C and gross calorific value of each RBOBD blend and diesel were tested at Faculty of Chemical Engineering, Universiti Teknologi Malaysia. Table 1 shows the RBOBD proportions in diesel while Table 2 shows the physical properties of the tested fuels.

Table 1 Biodiesel Blends

Fuel Label	Volume of RBOBD (L)	Volume of CDF (L)	Total (L)
B0	0	9	10
B5	0.5	9.5	10
B15	1.5	8.5	10
B25	2.5	7.5	10

Table 2 Physical Properties of Diesel and RBOBD Blends

Property	ASTM	B0	B5	B15	B25
Density at 15° C (kg/m^3)	D941	815	820	824	829
Kinematic Viscosity at 40° C (mm^2/s)	D445	3.55	3.63	3.73	3.81
Surface Tension at15° C (N/m)	D971	0.0267	0.0275	0.0278	0.0281
Gross Calorific Value (kJ/kg)	D240	45.69	45.43	44.96	44.13

2.2 Experimental Setup

The experimental setup for combustion performance tests included an Industrial Light Oil Burner, K-type thermocouples, a standard spray nozzle, 1 m cast cement insulated open-ended combustion chamber, a Midi temperature data logger, the LCA 6000 air speed indicator and the Horiba Enda 5000 gas analyzer. The oil burner was attached at the inlet of the combustion chamber to blow air and ignite the fuel. Eight equal distant (100 mm apart) thermocouples were mounted on the combustion chamber. K-type thermocouples were connected with Midi Temperature data logger to display the wall temperature in Celsius (°C). The standard nozzle was fixed to spay the fuel inside the combustor. The nozzle sprays the fuel with the pressure of 6.8 bar at the flow rate of 5.68 L/h. Figure 2 shows the schematic diagram for the experimental setup while Figure 3 shows the photograph of the open-ended combustion chamber. Figure 4 depicts the spray nozzle used in these experiments.

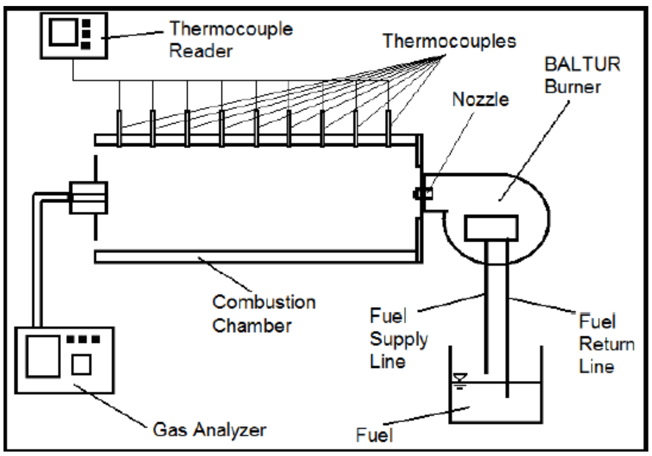

Figure 2 Diagram of Experimental Setup

Figure 3 Experimental Setup Rig

Figure 4 The Standard Spray Nozzle

The emission chamber was connected to the exhaust part of the combustion chamber which had the emission sensors to detect the emissions from combustor. Horiba Enda 5000 gas analyzer then receives the electrical signal from the emission sensor and displays the emissions e.g. CO, SO_2 and NO_x. For flow of air, air speed indicator was used. Three equivalence ratios i.e. 0.8 (lean fuel mixture), 1.0 (stoichiometric fuel mixture) and 1.2 (rich fuel mixture) were used in the combustion test.

3.0 RESULTS AND DISCUSSION

3.1 Fuel Properties

As biodiesel percentage increases in the diesel, the physical properties such as density, kinematic viscosity and surface tension increase, while calorific value decreases (shown in Table 1). The density of fuel depends on the molecular structure and fatty acid contents. The unsaturated FAME in RBOBD is found in enormous quantity, which leads to higher density [27]. Similarly, higher viscosity in RBOBD blends is due to the single bond configuration between carbon and hydrogen atoms. The single bond allows more hydrogen atoms to attach carbon chain which makes the fuel more viscous. The surface tension of RBOBD blends is also higher than diesel because the RBOBD has stronger intermolecular attraction which leads to higher surface tension. On the other hand, calorific value of RBOBD blends is lower due to the addition oxygen molecule in biodiesel structure. Owing to additional oxygen in RBOBD structure, the cetane number, which is the indication to faster combustion, improves and ignition delay is reduced.

3.2 Wall Temperature Profiles

Wall temperature profile is effected by fuel to air equivalence ratios for diesel and RBOBD blends during combustion. By increasing the equivalence ratio from 0.8 to 1.0, the combustion condition changed from a lean fuel mixture to stoichiometric fuel mixture, and then from 1.0 to 1.2, the combustion condition changed to rich fuel mixture. Thus, the volume of air flow decreased as the fuel flow rate increased. In all experimented fuels, the higher wall temperature was witnessed at equivalence ratio (Φ = 1.2). Owing to more fuel is burned at fuel rich mixture conditions, more heat is released during combustion [28]. Therefore, the temperature profile pattern for biodiesel blends and diesel is similar to each other as shown in Figure 5(a), Figure 5(b) and Figure 5(c).

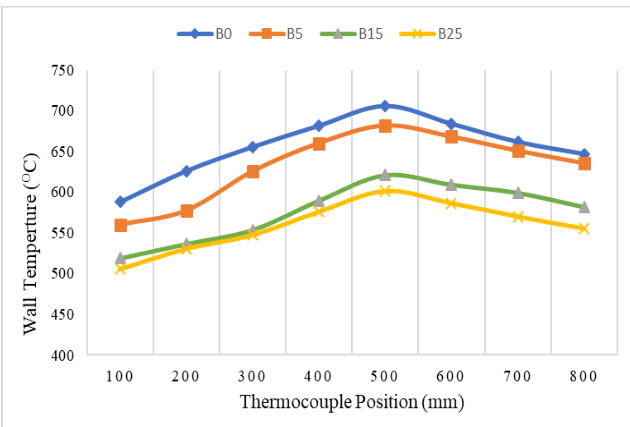

Figure 5 (a) Wall Temperature vs Thermocouple position at ϕ=0.8

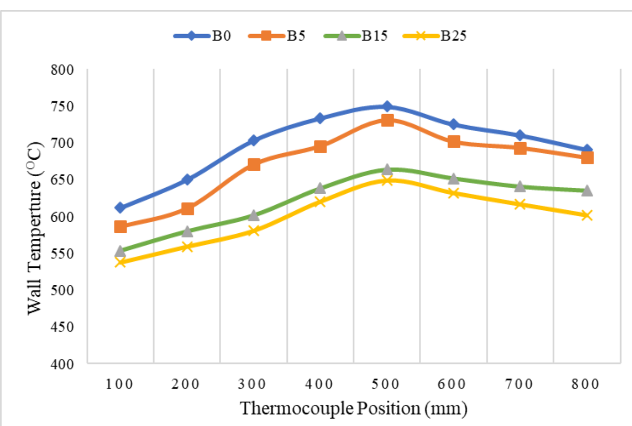

Figure 5 (b) Wall Temperature vs Thermocouple position at ϕ=1.0

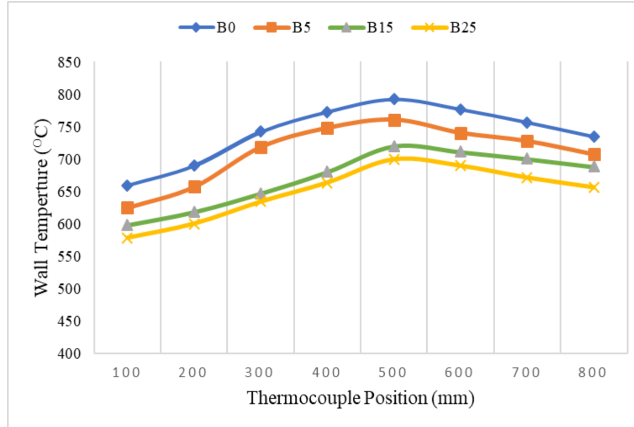

Figure 5 (c) Wall Temperature vs Thermocouple position at ϕ=1.2

It can be noted from above figures that the pattern of temperature profile in every equivalent ratio is almost similar. As the distance of thermocouple increases away from the burner, the wall temperature increases rapidly till the distance of 500 mm. This is because the fuel and air are combusted homogeneously, thus, it can be said that the mixture of fuel and air is complete/full. But once the distance of thermocouple from the burner passes 500mm, the wall temperature drops which shows that the flame is nearing its tip.

Furthermore, the graphs depict that B0 (i.e. CDF) has the greatest wall temperature in all cases, followed by B5, B15 and B25. Owing to higher calorific value of B0, the wall temperature remains at the top. On the other hand, for this blend the wall temperature of B25 shows lowest wall temperature as compared to other fuel blends tested because it has the lowest calorific value. Moreover, from lean mixture graph (i.e. Equivalent Ratio< 1) the maximum temperature attained by B0 is 728.9°C which is 3.43% greater than B5 (670°C), 11.98% greater than B15 (i.e. 641.8°C) and 13.6% greater than B25 (i.e. 629.8°C). On the other hand, rich fuel mixture follow the same pattern to lean mixtures as well. The highest temperature of B0 (i.e. 798°C) is 4.04% greater than B5 (760°C), 9.09% greater than B15 (720°C) and 11.61 % greater than B25 (i.e. 699.9°C). Though, at equivalent ratio, Φ = 1.0, the wall temperatures are moderate to lean and rich mixture, yet B0 has greater temperature than other tested fuels.

3.3 Gaseous Emission Profile

3.3.1 NO_x Emission

Figure 6 illustrates the NO_x emission of CDF and RBOBD blends against different equivalent ratios. The diesel fuel exhibits the lowest NO_x emissions as compared to the RBOBD blends while B25 has the highest NO_x emissions. The graph pattern of NO_x emission for every fuel follows similar trend.

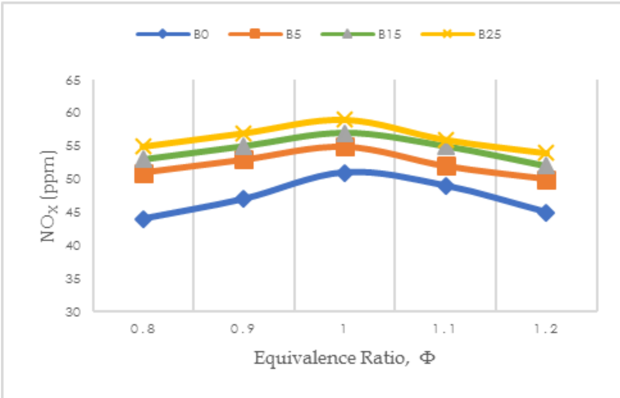

Figure 6 NOx Emission for different fuels

The NO_x emission rises steadily in the lean fuel mixture region, then reaches the highest value at the stoichiometric fuel mixture and then drops in the rich fuel mixture region. The highest value of NO_x that B25 attains is 59 ppm which is almost 15.67% higher than diesel's maximum value i.e. 51 ppm, 7.27% higher than B5 value i.e. 55 ppm and 3.50% higher than B15 value i.e. 57 ppm. RBO blends produces higher NO_x emissions than CDF because of the additional oxygen molecules present in the chemical structure of RBOBD [19]. This is why the NOx emission is greater for B25 even though the wall temperatures showed otherwise. The same trend was observed for other blends also.

3.3.2 CO Emission

CO emission of RBOBD blends and CDF is compared at different equivalent ratios and is shown in Figure 7. The graph pattern is almost similar for every fuel tested i.e. CO emission decreases rapidly in lean fuel mixture till equivalent ratio reaches at 1.0 and increases rapidly as equivalent ratio crosses 1.0 (rich fuel mixture). The lowest CO emission was inspected at stoichiometric fuel mixture for every fuel. Among the tested fuels, diesel produces highest CO emission while B25 emits lowest amount. The minimum amount of CO that B25 emit is 8 ppm which is 33.33% lower than B15 (i.e. 12 ppm), 46.66% lower than B5 (i.e. 15 ppm) and 68% lower than diesel (i.e. 25 ppm).

B25 emits lowest CO emission because there is extra oxygen present in the RBOBD chemical structure, which helps in producing CO_2 instead of CO, hence complete combustion occurs. Moreover, Liaquat *et al.* [29], by means of experiments, observed that CO forms when there is scarce air supply which results in incomplete combustion. The dearth of air is in the rich fuel mixture, that's why CO emission increases rapidly as the equivalent ratio crosses 1.0.

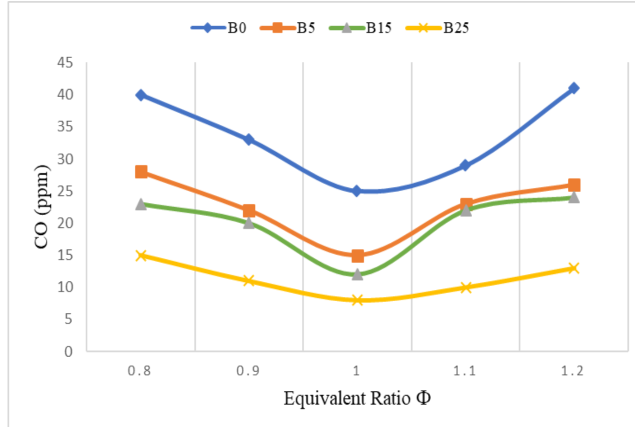

Figure 7 CO Emission for different fuels

3.3.3 SO_2 Emission

SO_2 emission of RBOBD blends and CDF is compared at different equivalent ratios, and is depicted in Figure 8. For every tested fuel, SO_2 emission increases in lean fuel mixture till stoichiometric fuel mixture and decreases steadily in rich fuel mixture. The highest SO_2 emissions are found at equivalent ratio, $\Phi = 1$. Among the fuels, diesel produces 14 ppm of SO_2 which is 14.28% higher than B5 (i.e. 12 ppm), 28.57% higher than B15 (i.e. 10 ppm) and 50% higher than B25 (i.e. 7 ppm). Croise and Thambimuthu [30] analysed that the higher amount of SO_2 is produced when the temperature and oxygen concentration is high. From Figure 8, SO_2 emission is increasing because the temperature is high and air is in excess quantity as compared to fuel. On the other hand, the SO_2 emission is decreasing in the rich fuel mixture because there is no additional air for SO_2 formation. Furthermore, the biodiesels contain very small amount of sulphur as compared to petroleum products, thus, the RBOBD blends emit lower SO_2 emission than diesel.

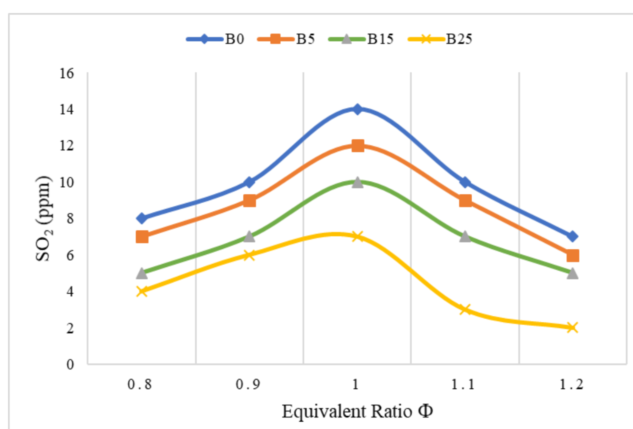

Figure 8 SO_2 Emission for different fuels

4.0 CONCLUSIONS

The combustion experiments of RBOBD blends were conducted in an oil burner and compared with diesel at different equivalence ratios. Physical properties such as density, kinematic viscosity, surface tension, and calorific value were studied for RBOBD blend and diesel. Then, all fuels were combusted at various equivalence ratios to obtain the wall temperature, NO_x, SO_2, and CO emission profiles. It is concluded that, as RBOBD concentration increased in diesel, the density, kinematic viscosity and surface tension increased while calorific value decreased. The RBOBD blends enhanced the fuel combustion efficiency at lower temperatures. The increase of RBOBD proportion in diesel reduced the emissions of SO_2, and CO. The results of the study can be summarized with the following observations:

- For all equivalence ratios, RBOBD blends combusted at lower temperatures than diesel.
- RBOBD blends showed lower CO and SO_2 emissions.
- Decrement in the air volume was witnessed as the fuel consumption increased, which generated more heat energy during the combustion.

Acknowledgements

The authors would like to thank the Ministry of Higher Education of Malaysia and Research Management Center, Universiti Teknologi Malaysia (project number: 17H47) for the research grant to undertake this project. The authors would also like to thank the Faculty of Mechanical Engineering, Universiti Teknologi Malaysia for providing the research facilities and space to undertake this work.

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