

Macroscopic spray characteristics of palm oil-diesel blends in a constant volume combustion chamber

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Concern with fossil fuel depletion and environmental degradation promotes the use of renewable energy sources in particular bio-fuel for automotive and power generation. Palm oil in its refined form as cooking oil can be used as fuel in diesel engines. Present study evaluates macroscopic spray characteristics, such as tip penetration, cone angle and spray area using direct injection diesel injector in a constant volume combustion chamber. Palm oil blend with diesel at 20, 40, 60, and 80 % as well as pure palm oil (100 %) and diesel were tested separately using direct visualization technique. Spray developments were investigated at elevated injection pressure starting from 20 MPa (original setting) to 30 and 34 MPa (maximum pressure). Experimental results for palm oil blends show that, spray development process is highly affected with increasing palm oil in the blend. Spray tip penetration and cone angle of blends were found to decrease by about 50 and 30 % respectively compared to diesel fuel. At elevated injection pressures, spray characteristics of the blends show significant improvement. Tip penetration and spray area for P20 at 34 MPa were comparable to diesel at its original injection pressure setting. Moreover, blends average cone angles were found larger at 30 MPa, by about 14.93, 11.47, 7.34 and 1.84 % for P20, P40, P60 and P80 respectively. For P20, 34 MPa injection pressure is sufficient to display spray characteristics similar to diesel, but require higher than 34 MPa injection pressure for other blends.

Keywords: Palm oil blends, bio-fuel, spray characteristics

Introduction

Palm oil can be used as alternative fuel in compression ignition (CI) engine, either neat or blended with diesel in a certain proportion without or limited modification to the engine. Several experimental investigations have been done on combustion and emission characteristics of neat and blended diesel fuel with palm oil in diesel engines^{1,2}. High viscosity and polymerization of vegetable oil at high temperature produced heavy low-volatility compounds that are difficult to combust initially in the main combustion phase, but produce longer combustion period in the late combustion phase². Palm oil composition also produced higher CO and NO emissions². The air-fuel mixing process is highly affected by the difficulty in

atomization, especially for heavy compound fuel. Higher CO will be produced due to lack of oxygen in a locally rich mixture during combustion process. Most researchers suggest preheating high viscosity oil slightly above 50°C before injection into the combustion chamber³⁻⁵. However, using high temperature beyond the usual fuel injection pump operating temperature may damage the injection pump. Previous study revealed that preheating of crude palm oil (CPO) does not benefit engine performance except avoid clogging and maintaining smooth fuel flow². Therefore, effect of preheating the fuel still need more careful study, and will not be done in this work.

In spite of these studies on palm oil fuel properties and their effect on combustion and emissions, no studies were done on its spray characteristics. Studies on spray characteristics of various fuels in diesel engine are

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necessary as they indicate directly combustion and hence engine performance. Combustion efficiencies rely significantly on quality of air/fuel mixture, which is dependent on fuel injection into the combustion chamber. All of the injected fuel should be in contact with maximum amount of oxygen available, to ensure complete and fast combustion. Moreover, emission levels can also be reduced by enhancing the spray characteristics and quality of air/fuel mixing. Using direct visualization methods, macroscopic parameters such as tip penetration, cone angle and spray area can be determined. Direct visualization method is the most frequently used technique for fuel spray and combustion characteristic studies. This technique was previously reviewed⁶ and used to study macroscopic spray and combustion characteristics of diesel⁷⁻¹², gasoline¹³, ethanol-gasoline blends¹⁴, natural gas and hydrogen¹⁵, and biodiesel fuel¹⁶⁻²². Fuel spray and combustion process in IC engines can be simulated in a high pressure and temperature constant-volume vessel where shadowgraph photographs of fuel spray and combustion process can be acquired using a high-speed digital camera⁶. The purpose of this study is to investigate the effect of high viscosity palm oil and its blends on spray characteristics in a direct injection constant volume combustion chamber. In order to investigate the influence of palm oil blends on the spray characteristics, the fuel mass injected and spray characteristics were determined experimentally at three injection pressures; 20, 30 and 34 MPa, using direct visualization technique. In addition, the physical properties of palm oil and its blends were studied in accordance with ASTM standards.

Experimental Section

Spray Visualization System

Optical measurement setup that was used in the experiments is described with the objective to measure spray tip penetration, spray cone angle and spray area. Tip penetration is defined as maximum distance to which the spray can reach away from the nozzle tip. While, spray cone angle is the angle formed by the cone of liquid spray, and spray area is the measurement of the size of spray region. The optical measurement setup used in the liquid fuel penetration is a constant volume vessel with an optical access to observe the spray development process from direct injection diesel injector. The constant volume combustion chamber is equipped with an optical access window made of fused silica, fuel injector, pressure relief valve, and intake and exhaust valves.

Most of researchers prefer to use either high pressure pump^{7,8-12,17,20} or high pressure nitrogen gas to increase the pressure of fuel in the accumulator before being fed to the injector^{13-14,22}. High pressure fuel flow and the injection duration were controlled by a solenoid/electronic injector. However, in this work, a pneumatic cylinder was used to produce high pressure fuel, to energize the injection process. A modified mechanical single hole nozzle (YANMAR YDLLA-P type) fuel injector of 0.8 mm diameter that has minimum 20 MPa injection pressure was used to create the fuel spray. In order to create the injection pressure, Bosch type, YANMAR PFE-M type fuel injection pump was used. Once the compressed air is supplied to the pneumatic cylinder, the cylinder rod will push the fuel pump. The increasing pressure inside the fuel line will overcome the spring force inside the injector and produced fuel spray at the injector nozzle. The pressure supplied to the pneumatic cylinder was set at 0.8 MPa, taken from a compressor. Injection starting pressure can be varied by increasing or decreasing the thickness of adjusting shims of the injector. In this work, the starting injection pressures were studied at 3 different injection pressures; 20, 30 and 34 MPa. Maximum setting for the injection pressure is 34 MPa, based on the maximum adjusting shim of 0.8 mm.

The fuels used were refined palm oil (RPO) and the blend with diesel varied from 20, 40, 60, 80 and 100% palm oil, identified as P20, P40, P60, P80 and P100 respectively. The viscosities of the fuels used were determined using Brookfield viscometer (Brookfield, DV-I+). The calorific values were determined using an adiabatic bomb calorimeter (Yoshida Seisakusho, 1013-B) and the densities were determined where a constant volume of oil is weighed. Mass of fuel injected was also measured as it would affect fuel spray development. The mass of fuel injected were determined at three different starting injection pressures, 20, 30 and 34 MPa at a fixed maximum pump control lever.

The palm oil blends spray characteristics was compared to neat diesel spray in the experiments. Pressure of the constant volume vessel was set at 0.2 MPa with temperature of 300 K. Measurements of the liquid fuel penetration were observed via direct visualization technique and the spray development was recorded using high speed camera (Olympus, I-Speed 2). The visualization of digital imaging either in steady state or continuous recording can be employed to expose the conditions of the spray process. The macroscopic parameter such as spray geometry, penetration depth and subsequent combustion can be

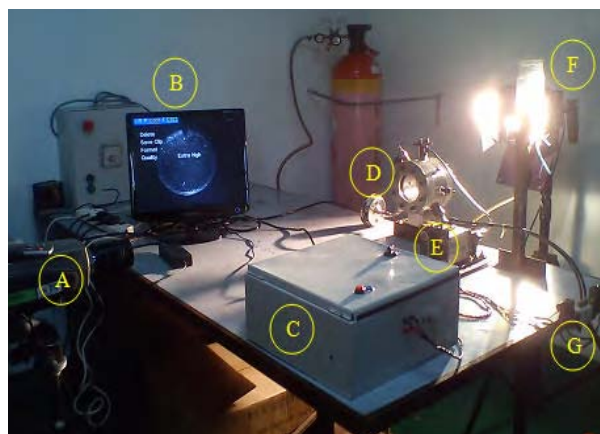


Fig. 1: Experimental setup for spray visualization

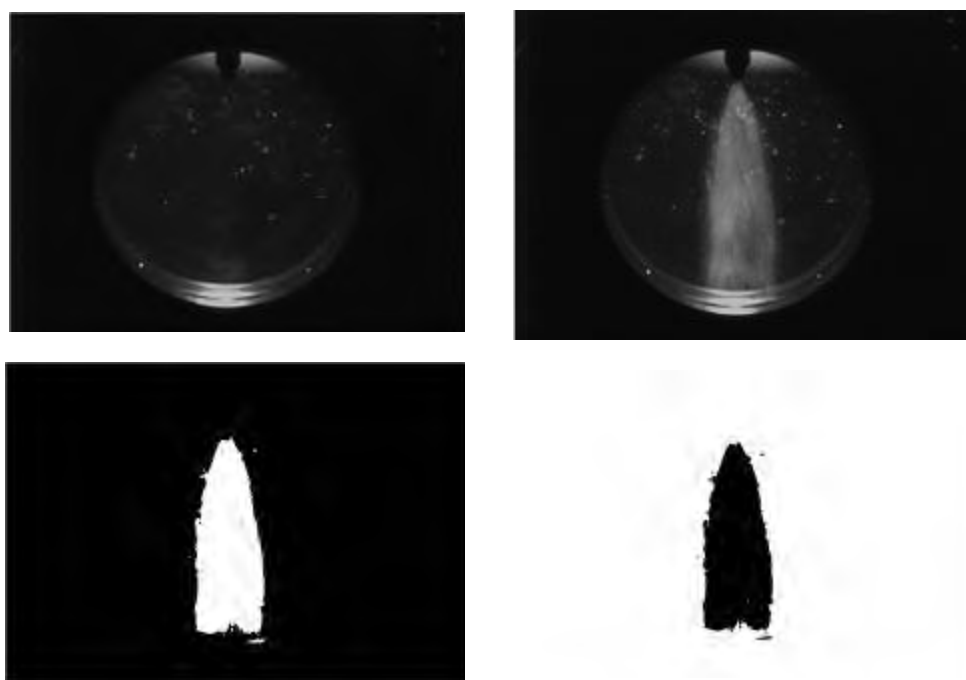


Fig. 2—Spray area calculation using image processing

exposed using this technique. In this work, digital images of the spray were acquired using a high speed camera, that is placed at a 90 degree angle to the optical window, supported by 1000 W light source. Experimental setup for spray visualization shown in Fig. 1, consists of A- high speed camera, B- camera monitor, C- controller, D- constant volume combustion chamber, E- pneumatic cylinder and fuel pump F- lighting source and G- solenoid valve. Digital images of the spray development were measured using CAD software (SolidWork 2010 SP0.0) to obtain macroscopic spray parameters such as tip penetration and cone angle. In case of spray area, it was measured using MATLAB® with image enhancement, subtraction, segmentation, and

morphological processes. The process started with image enhancement and conversion into grey scale format followed by image subtraction to produce an image with plain background. The first filtering process is known as segmentation or thresholding that produces a binary image which is formed from object pixels. Generally the object pixels are black with white background. Morphological operation is used to regularize or clean the binary images. Finally, the spray area is calculated by defining the area as number of pixels with the value '1' in a binary image and the area is calculated by summing the areas of each pixel in the image. Area of an individual pixel is determined by looking at its 2-by-2 neighborhood. Fig. 2 shows the image processes

Table 1—Physical properties of palm oil blends

Indication	Density kg/m ³	Calorific value (kJ/kg)	Viscosity (mm ² /s)	Viscosity Reduction (%)
P100	904	39,027	59.68	-
P80	896	40165	50.93	14.66
P60	882	41,184	45.90	23.08
P40	863	41,558	27.32	54.23
P20	855	42,840	24.55	58.87
Diesel	840	43,379	13.95	-

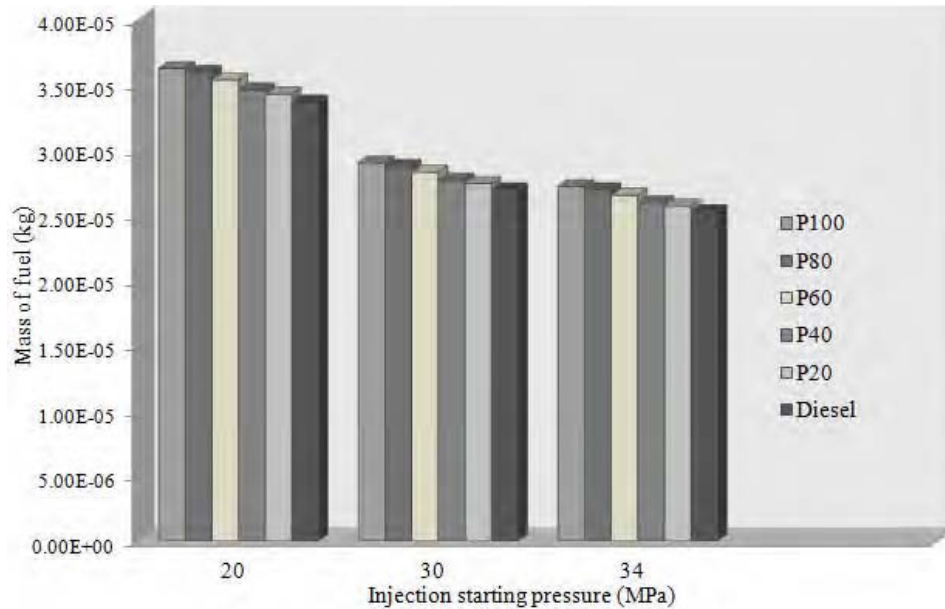


Fig. 3—Mass of fuel injected at different injection pressures

to obtain spray area (a) Gray level comparison image; (b) Gray level spray image; (c) binary image after noise removal; (d) Inverted image to calculate spray area (subtraction of total image size with white area).

Results and Discussion

Fuel Properties and Mass of Fuel Injected

Density, viscosity and calorific value measurements of diesel and its blend with palm oil are given in Table 1. Higher viscosity would significantly affect the fuel spray structure due to poor atomization. Viscosity of palm oil is 59.68 mm²/s, which is about 4.27 times higher than diesel fuel. High viscosity of palm oil is due to presence of unsaturated fatty acid and high molar mass of vegetable oil in the range of 600-900 g/mol, which is about 20 times higher than diesel fuel. The volume of fuel injected were observe at 20, 30 and 34 MPa injection pressures with fixed pump control lever in a 0.2 MPa constant volume vessel. The volume of fuel injected was

found to be 4.0×10^{-2} , 3.2×10^{-2} and 3.0×10^{-2} ml for injection pressures of 20, 30 and 34 MPa respectively. At higher starting injection pressure, the volume of fuel injected decreases due to shorter injection duration. Shorter injection duration at higher injection pressure is expected due to faster closing time of nozzle valve in the injector that was forced by nozzle spring. Different amount of mass fuels injected at various starting injection pressure is shown in Fig 3. From the experiment, it was found that P100 has the highest mass of fuel injected when compared to other fuels due to higher density compared to diesel.

Macroscopic Spray Characteristics

Spray characteristics of diesel and palm oil blends were studied to investigate the effect of high viscosity fuel on spray development and macroscopic characteristics. The shadowgraph spray development process comparison of diesel and various palm oil blends

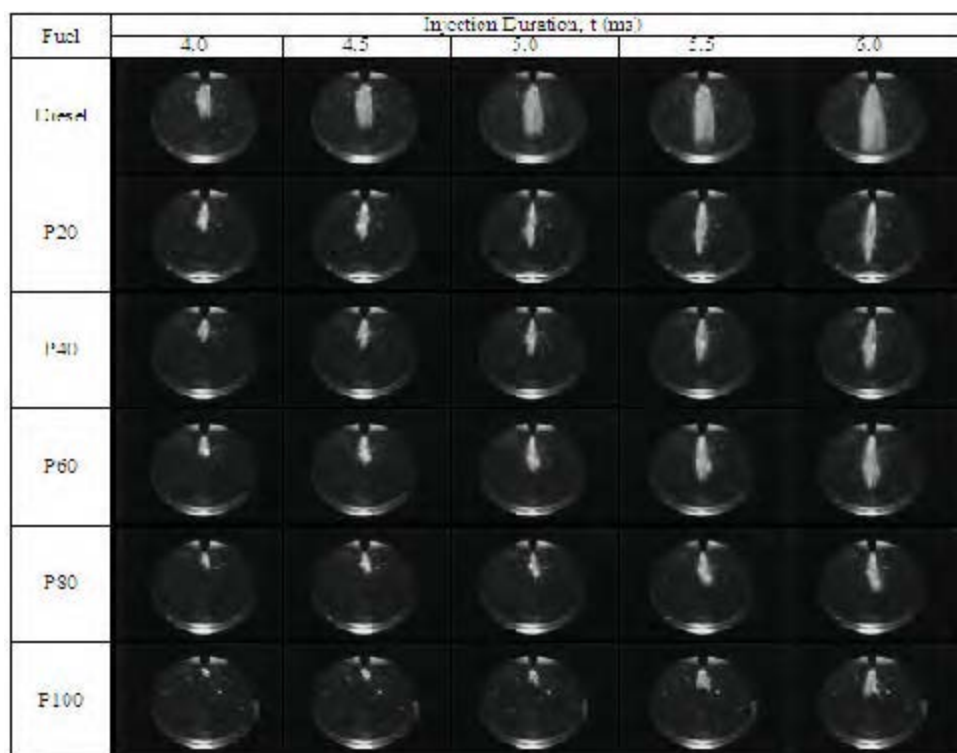


Fig. 4—Spray development of diesel and palm oil blends at 20 MPa injection pressure

at 20 MPa injection pressure as a function of time is shown in Fig 4. Blending of palm oil shows slower spray evolution compared to diesel. Cone angle for blends are also smaller but improved at P20. The slower spray evolution of blended fuel is due to higher viscosity of palm oil, indicating higher resistance to fuel flow. Fuel spray tip penetration, cone angle and spray cone area are required to characterize overall spray structure. Fig. 5a shows the spray tip penetrations for all fuels at 20 MPa injection pressure. Experiment data shows that initially the spray penetrates almost linearly with time for all fuel. Diesel spray had the longest spray tip penetration and P100 had the shortest under the same condition. Experiment also exposed that P20 has the highest tip penetration among the other blends. The blends average tip penetration degradation was found to be about 26.47, 33.68, 40.33, 47.61 and 54.84 % for P20, P40, P60, P80 and P100 respectively. Tip penetrations of the blends show slow increments at the early stage of injection duration due to high shear forces for higher viscosity. Tip penetration increments became almost linear with time in the middle of injection duration as it has overcome the shear forces but again slowdown as it headed for the spray impact zone. Higher viscosity of blend fuel needs to overcome friction between the fuel

and nozzle surface, which affects spray development. In case of diesel fuel, it is easier for the spray to breakup and form droplets when compared to blends.

Fig. 5 also shows the spray tip penetration of palm oil blends at different injection pressures. When the injection pressure was increased to 34 MPa, the increment of spray tip penetrations increased significantly for all fuels. It can be observed that higher injection pressures and lower blend ratios improve spray tip penetration and tip increment for the blends. Tip penetration of P20 at 34 MPa was found to be very close to diesel at 20 MPa, by about 0.04 %. For other blends, average tip penetration degradation was found to be about 0.11, 0.17, 0.23 and 0.35 % for P40, P60, P80 and P100 respectively. Based on this result, it can be concluded that, 34 MPa injection pressure is suitable for P20. However, for other blends it is not possible to find the suitable injection pressure as it has reached the maximum pressure. Therefore, higher injection pressure injector is needed to find suitable injection pressure for P40, P60, P80 and P100. In conclusion, the effect of injection pressure on spray tip penetration suggest that increasing the injection pressure for palm oil and its blends is necessary to ensure maximum air contact with fuel is achieved.

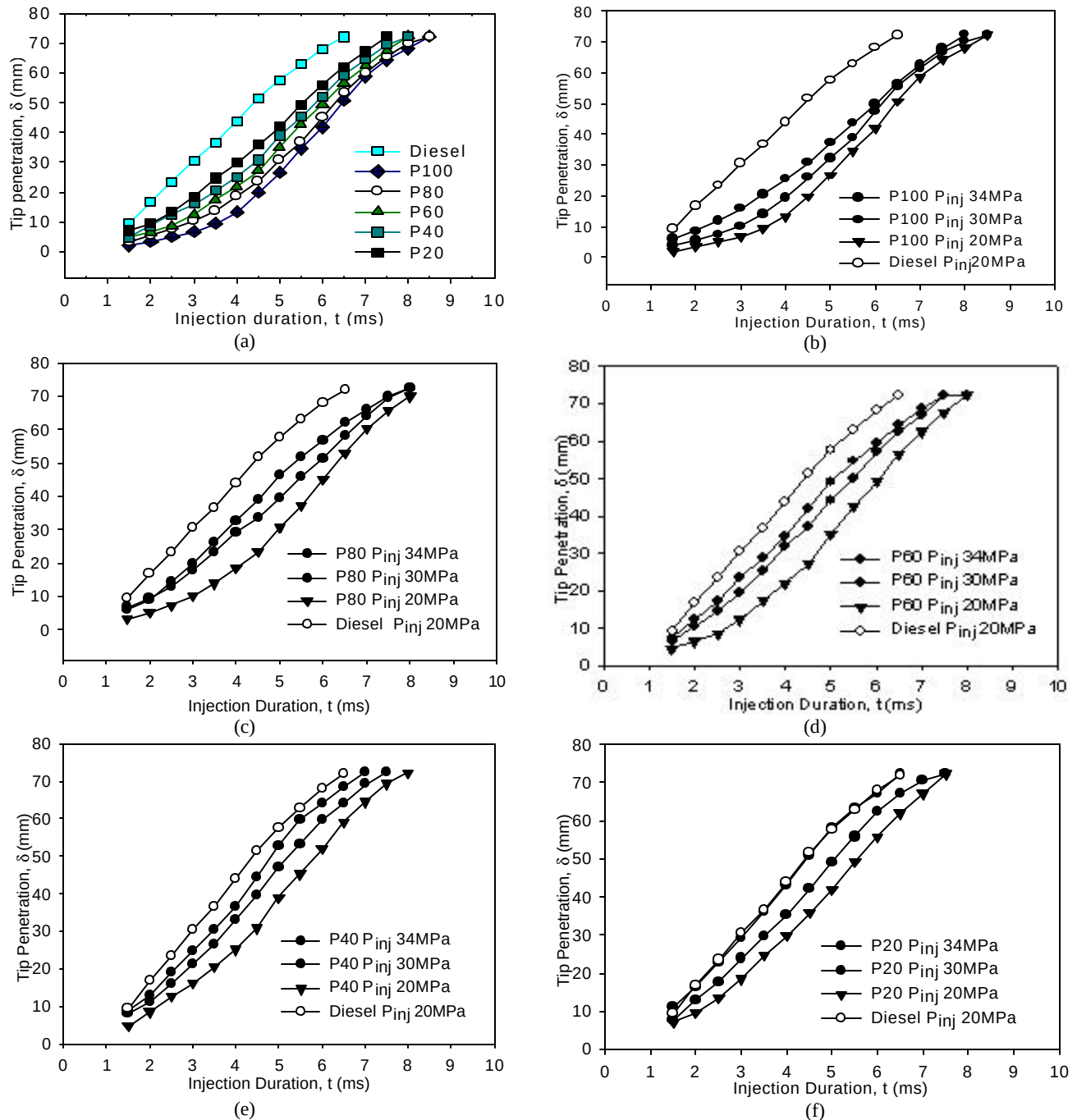


Fig. 5—Spray tip penetration (a) comparison between palm oil blends and diesel at 20 MPa injection pressure and blends spray tip penetrations at various injection pressure for (b) P100, (c) P80, (d) P60, (e) P40 and (f) P20

The viscosity of palm oil and its blend also has major influence on the spray cone angle. Spray cone angle of palm oil and its blends at 20 MPa were compared to diesel as shown in Fig. 6a. The spray cone angle remains nearly constant during the whole injection duration as suggested by Delacourt²³ for diesel spray cone angle, as well as for blends. The magnitudes of spray cone angle of blends decrease with increase of palm oil

fraction in diesel fuel. Spray cone angles for all blends were found to be smaller, with average cone angle reduction by about 15.30, 12.77, 15.00, 22.15 and 28.56 % for P20, P40, P60, P80 and P100 respectively. The average spray cone angle for P0, P20, P40, P60, P80 and P100 were investigated at various injection pressures as shown in Fig. 6b. The changes of cone angle for palm oil blends are obvious due to different viscosities. It was

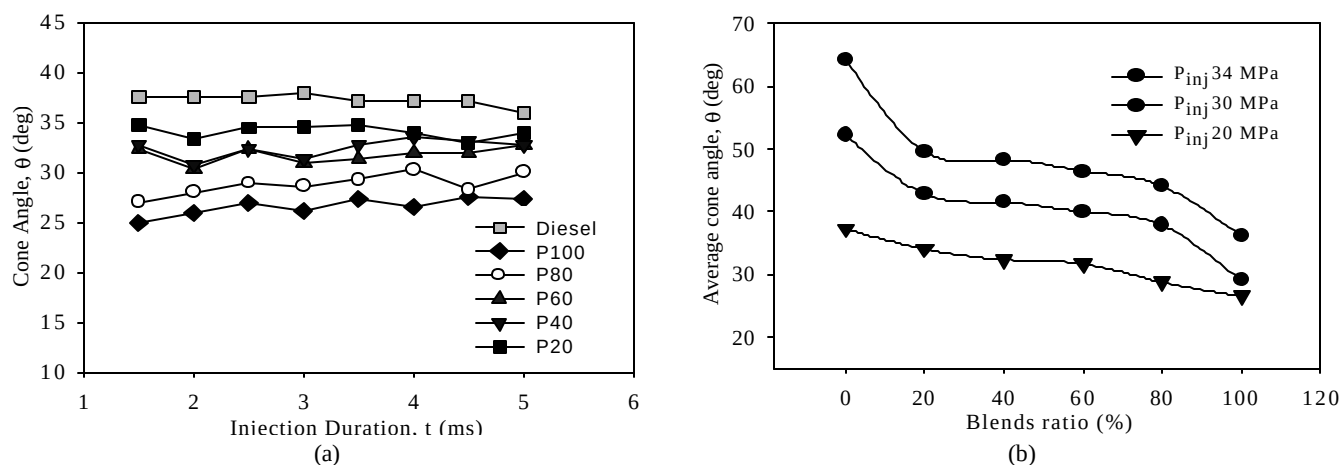


Fig 6—Spray cone angle (a) comparison between palm oil blends and diesel at 20 MPa injection pressure and (b) average cone angle at various blends ratio and injection pressure

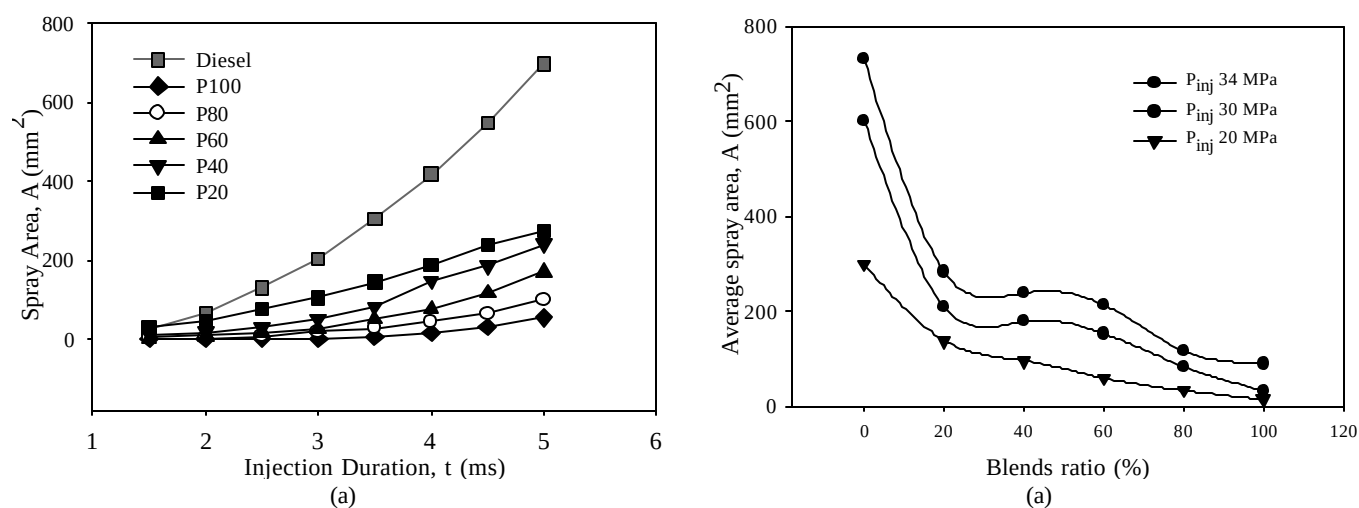


Fig 7—Spray area (a) comparison between palm oil blends and diesel at 20 MPa injection pressure and (b) average spray area at various blends ratio

found that increasing injection pressure increases spray cone angle for both diesel and palm oil blends. Except for P100, cone angles for all blends were improved more than diesel (at standard injection 20 MPa), when the injection pressures were increase to 30 and 34 MPa. For P100, spray cone angle is nearly constant in the range of 25 to 38 ° due to its high viscosity that resists the fuel from breaking-up during injection process. Furthermore, it was observed that lower blend ratios improve spray cone angle as shown in Fig. 6b.

Some authors have characterized the evolution of the spray area, and it represents the quality of the air-fuel mixing. Fig. 7a shows that at 20 MPa injection pressure, spray area grows as a function of injection duration, similar to spray tip penetration and cone angle. The largest spray area was observed for diesel fuel at

20 MPa injection pressure. In case of palm oil blends, spray areas increase with decrease in blend ratios showing better air-fuel mixing. Further observation of spray areas at various injection pressures show significant improvement after the injection pressures were increase up to 34 MPa for all blends. Fig. 7b shows that average spray areas for all blends were found to be smaller when compared to diesel even after the injection pressure were increased up to 34 MPa. However, P20 shows a major improvement as its spray area was closed to diesel (standard injection pressure). As for P100, the spray area does not reach 100 mm² thus indicating poor air-fuel mixing that lead to poor combustion. Blend spray areas were found to increase with increasing injection pressures and decreasing blend ratios, indicating better spray area with smaller fraction of palm oil in the blends, as shown in Fig. 7b.

Conclusion

Spray structure of non-evaporating palm oil blends was investigated by using direct visualization technique. A pneumatic cylinder was used instead of using high pressure pump or high pressure nitrogen gas to energize the injection process. The following conclusions were reached that i) it was found that high viscosity of palm oil influence spray shape evolution, spray tip penetration, spray cone angle and spray area; ii) tip penetration of the blends was found to be shorter by about 50 % at standard injection pressure when compared to diesel, but improved when the injection pressure were increased to 34 MPa. At 34 MPa injection pressure, P20 shows significant increment and nearly achieves the same diesel tip penetration at standard injection pressure. Spray cone angles for all blends were found to be lower by about 30 % than conventional diesel, but increase beyond the diesel cone area after the injection pressures were elevated to 30 and 34 MPa and iii) other than preheating the fuel, advancing injection timing and increasing injection starting pressure are recommended whenever palm oil or its blends is used in IC engines, as it will enhance the air-fuel mixing thus increase the engine performance and the same time lowered the engine emissions. It can be conclude that higher injection pressure (more than 34 MPa) and lower mass fraction of palm oil improves spray characteristics of palm oil blends.

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References

- Almeida S C A, Belchior C R, Nascimento M V G, Vieira L S R & Fleury G, Performance of a diesel generator fuelled with palm oil, *Fuel*, **81** (2002) 2097-2102.
- Bari S, Lim T H & Yu C W, Effects of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine, *Renew Energ*, **27** (2002) 339-351.
- Prasad C M V, Krishna M V S M, Reddy C P & Mohan K R, Performance evaluation of non-edible vegetable oils as substitute fuels in low heat rejection diesel engines, *P I Mech Eng D-J Aut*, **214** (2000) 181-188.
- Bari S & Roy M M, Prospect of rice bran oil as an alternative to diesel fuel, *Proceed of the Fifth Inter Conf on Small Engines, their Fuels and the Environment* (University of Reading, United Kingdom) 1995, 31-36.
- Ahmad H H & Salmah J, Preliminary observations of using palm oil as fuel for cars fitted with elsbett engine, *PORIM Inter Biofuel Conf* (Palm Oil Research Institute of Malaysia) 1995, 92-96.
- Soid S N & Zainal Z A, Spray and combustion characterization for internal combustion engines using optical measuring techniques – A review, *Energy*, **36** (2011) 724-741.
- Bougie B, Tulej M, Dreier T, Dam N J, Ter Meulen JJ *et al*, Optical diagnostics of diesel spray injections and combustion in a high-pressure high-temperature cell, *Appl Phys B-Lasers O*, **80** (2005) 1039-1045.
- Yoshizaki T, Yamamoto O, Nishida K, Hiroyasu H & Suzuki M, Evaporating spray and flame distributions in the combustion chamber of a direct injection diesel engine, *JSAE Review*, **18** (1997) 219-224.
- Klein-Douwel R J H, Frijters P J M, Somers L M T, de Boer W A & Baert R S G, Macroscopic diesel fuel spray shadowgraphy using high speed digital imaging in a high pressure cell, *Fuel*, **86** (2007) 1994-2007.
- Gao J, Moon S, Zhang Y, Nishida K & Matsumoto Y, Flame structure of wall-impinging diesel fuel sprays injected by group-hole nozzle, *Combust Flame*, **156** (2009) 1263-1277.
- Kostas J, Honnery D & Soria J, Time resolved measurements of the initial stages of fuel spray penetration, *Fuel*, **88** (2009) 2225-2237.
- Payri R, Salvador F J, Gimeno J & Zapata L D, Diesel nozzle geometry influence on spray liquid-phase fuel penetration in evaporative conditions, *Fuel*, **87** (2008) 1165-1176.
- Nishida K, Tian J, Sumoto Y, Long W, Sato K *et al*, An experimental and numerical study on sprays injected from two-hole nozzles for DISI engines, *Fuel*, **88** (2009) 1634-1642.
- Gao J, Jiang D & Huang Z, Spray properties of alternative fuels: A comparative analysis of ethanol-gasoline blends and gasoline, *Fuel*, **86** (2007) 1646-1650.
- Ishiyama T, Shioji M, Ihara T, Inoue T & Takada N, Characteristics of spontaneous ignition and combustion in unsteady high speed gaseous fuel jets, *SAE Paper 2003-01-1922* (2003).
- Wakai K, Nishida K, Yoshizaki T & Hiroyasu H, Spray and ignition characteristics of di-methyl ether injected by a DI diesel injector, *Proceed of the Fourth Inter Symp COMODIA*, **98** (1998) 537-542.
- Bang S H & Lee C S, Fuel injection characteristics and spray behavior of DME blended with methyl ester derived from soybean oil, *Fuel*, **89** (2010) 797-800.
- Fang T, Lin Y C, Foong T M & Lee C F, Biodiesel combustion in an optical HSDI diesel engine under low load premixed combustion conditions, *Fuel*, **88** (2009) 2154-2162.
- Fang T & Lee C F, Bio-diesel effects on combustion processes in an HSDI diesel engine using advanced injection strategies, *P Combust Inst*, **32** (2009) 2785-2792.
- Desantes J M, Payri R, Garc ya A & Manin J, Experimental study of biodiesel blends' effects on diesel injection processes, *Energ Fuel*, **23** (2009) 3227-3235.
- Pastor J V, Payri R, Gimeno J & Nerva J G, Experimental study on RME blends: Liquid-phase fuel penetration, chemiluminescence, and soot luminosity in diesel-like conditions, *Energ Fuel*, **23** (2009) 5899-5915.
- Suh H K, Roh H G & Lee C S, Spray and combustion characteristics of biodiesel/diesel blended fuel in a direct injection common-rail diesel engine, *J Eng Gas Turb Power*, **130** (2008) 032807.
- Delacourt E, Desmet B & Besson B, Characterisation of very high pressure diesel sprays using digital imaging techniques, *Fuel*, **84** (2005) 859-867.