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PHYSICAL PROPERTIES AND SPRAY CHARACTERISTICS OF ULTRASOUND-ASSISTED EMULSION BASED ON ULTRA LOW SULPHUR DIESEL AND BIODIESEL

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ABSTRACT

Using fuels with a no-sulphur or limited-sulphur content for diesel engines has been considered an urgent issue in the reduction of pollution due to the difficulty of controlling sulphur emissions. In this experimental study, ultra-low sulphur diesel (ULSD) originating from fossil fuel and biodiesel from waste cooking oil (WOB) were mixed with ultrasonic assistance. The optimal mixing rate of ULSD and WOB, and the optimal distance of the ultrasound horn tip, were found as 65%:35% and 80 mm, respectively. After 15 minutes of ultrasonic treatment, a ULSD-WOB emulsion was formed, with the highest stability at around 99%, and its physical properties attained constant values. In addition, the spray characteristics of the ULSD-WOB emulsion, the WOB and the ULSD, including the spray penetration and cone angle, were examined and compared to those of fossil diesel fuel (DF). As a result, the ULSD-WOB emulsion produced with the assistance of ultrasound met the strict requirements of fuels used for diesel engines.

Keywords: Biodiesel; Physical properties; Spray characteristics; Ultra-low sulphur diesel; Ultrasound

1. INTRODUCTION

Among transportation activities and sectors, the maritime industry continues to maintain its leading position due to its largest transport capacity. However, the emissions and various pollutant sources as a result of the use of fossil diesel fuel from ships and vessels engaged in maritime activities are considered as the main causes of pollution in the air (Damanik et al., 2017; Silitonga et al., 2017; Hossain et al., 2019). One of the emissions which causes serious pollution is sulphur-originated (SOx), which is difficult to control and recover due to its chemical properties, as well as the high cost involved (Zhao et al., 2018; Hoang, 2018). Reductions in sulphur emissions should be compulsory for engineers, manufacturers and policy makers, and advanced technologies need to be applied to diesel engines used in transport sectors, with the aim of meeting the strict regulations related to emissions (Damanik et al., 2018; Hoang, 2019; Hoang et al., 2019).

Currently, several solutions, including injection management; improvements to fuel supply systems; the use of low-sulphur or bio-based fuels; exhaust gas recirculation; the installation of scrubbers on exhaust lines; and the utilization of absorbent for sulphur emissions, are being used to reduce the pollution emissions from the diesel engines used in the transportation sectors

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(Hoang et al., 2019; Lin et al., 2010; Norhasyima et al., 2018).

However, while the use of low-sulphur fuels may be considered more suitable for existing diesel engines, ultra-low sulphur diesel fuel (ULSD) with a sulphur content lower than 0.0015% has been widely used for diesel engines in ships and vessels, especially ships being operated in SECA (Sulphur Emission Control Area) (Hoang & Pham, 2018). A disadvantage when ULSD is used for ships' diesel engines is that it is necessary to mount a cooling system in the fuel supply line, with the purpose of increasing three-fold the physical properties of the ULSD, as it has a lower viscosity and density than DF. This leads to the high level of initial investigation capital of the above-mentioned cooling system (Mangus et al., 2015). In addition, use of biodiesels (BD) is being encouraged for use in diesel engines, with the aim of promoting "Green Shipping" because of their advantages such as renewability, non-toxicity, and absence of sulphur biodegradation (Choi et al., 2016; Hwang et al., 2017; Hoang & Le, 2019a). However, they do also have some disadvantages, such as slightly high kinematic viscosity (KV) and density compared to DF (Silitonga et al., 2019). Due to the above-mentioned reasons, mixing two fuel types, such one with high viscosity (BD) and one with low viscosity (ULSD), may bring many benefits, including equal viscosity to DF; an increase in storage stability compared to BD (Kusumo et al., 2017); a decrease in cost due to the installation of the cooling system; and a reduction in the cloud point compared to BD (Milano et al., 2018). In particular, the increase in lubricity, the reduction of frictional losses and wear, and the reduction of injector nozzle erosion compared to ULSD were indicated by Keynejad et al. (2018). Therefore, mixing ULSD and BD can meet the standards of fuels used for marine diesel engines (Leong et al., 2016; Tang et al., 2018).

Regarding the mixing ULSD and BD, many advanced methods and techniques based on active or passive modes in order to increase its effectiveness in a microreactor, with the aim of producing a uniform mixture from two separate liquid phases, have been developed (Hessel et al., 2005). Among the active approaches, the use of the ultrasound technique is considered as an example which provides a non-contact method to create a new microstructure (Katou et al., 2005). Moreover, the application of this technique to the physicochemical synthesis process or microstructure devices for multiphase flow has shown significant advantages (Aljbour et al., 2009; Hübner et al., 2012) because the acoustic streaming, generated local hot spot, and jet formation are formed inthe medium cavities of the liquid-liquid phase, leading to the creation of bubbles by the cavitation mechanism (Rivas et al., 2012). The implosion of the cavitation-based bubbles occurs through shockwaves (Korkut et al., 2014). Therefore, two immiscible liquid-liquid phases are affected by ultrasound, resulting in them being broken down to create the emulsion (Wu et al., 2010; Mostafaei et al., 2016). Additionally, John et al. (2016) and Navickas et al. (2013) have used the ultrasound technique to produce an emulsion of water-diesel; their results show that the combustion characteristics of the emulsion of the water-diesel fuel was better than that of DF. In another study, Imazu & Kojima (2013) also reported the stability of the emulsion created by water-diesel fuel-vegetable oil based on an ultrasonic mechanism. Several other studies on the preparation of emulsions for biodiesel and low-viscosity fuels have been conducted using ultrasonic methods (Lin et al., 2008; Li et al., 2010). This study focuses on the preparation of ULSD-WOB emulsions by ultrasonic techniques, with evaluation of some of the physical properties of these emulsions, such as viscosity, density and surface tension, and comparison of the spray properties of diesel (DF), WOB and ULSD. The results obtained in the study could be used to conduct further experiments involving combustion in diesel engines before general use in diesel engines to control sulphur emissions and reduce environmental pollution.

2. MATERIALS AND METHODS

2.1. Materials

Biodiesel from waste cooking oil (WOB), ultra low sulphur diesel (ULSD) with a 0.001% mass of sulphur, and fossil diesel fuel (DF) (diesel fuel No.2 with 0.25% sulphur) were used. The WOB was biodiesel produced from waste cooking oil on a pilot scale in Vietnam, while the ULSD and DF were provided by the Vietnam National Petroleum Group (Petrolimex). DF has been commonly used for diesel engines in the transport sector, forestry and agricultural fields, and generator sets. The properties of WOB, ULSD, and DF are given in Table 1.

Table 1 Properties of WOB, ULSD, and DF at 30^{o}C

Property	Unit	ULSD	DF	WOB
Density, ρ	kg/m^3	832	852	883
Kinematic viscosity, KV	cSt	1.9	3.6	6.8
Surface tension, ST	N/m	24.4	25.2	26.5
Sulphur content	ppm	10	2500	1.7
Cetane number, CN		44	45	52
Low heating value, LHV	MJ/kg	42.5	44	39.5
Oxygen content	% mass	0	0	10.8

From Table 1, it can be clearly seen that three properties, the density (ρ), kinematic viscosity (KV) and surface tension (ST) of WOB, are higher than those of DF, whereas three properties of ULSD are lower than those of DF. However, the cetane number (CN) and lower heating value (LHV) of WOB and ULSD are comparable to DF. In particular, the sulphur content of WOB and ULSD is much lower than that of DF, and WOB has a 10.8% oxygen component. Mixing WOB and ULSD can result in the formation of a mixture with three properties (ρ, KV, ST), which are equal to those of DF.

2.2. Methods

In order to mix WOB and ULSD, a method assisted by ultrasound and the cavitation mechanism was used. The determination of the mixing rate of WOB and ULSD was calculated by Equation 1 (Pham et al., 2018), which is based on the correlation of KV.

$$\ln KV = x_1 \ln KV_1 + x_2 \ln KV_2 + ... + x_n \ln KV_n \qquad (1)$$

where KV_i is the kinematic viscosity of component i; and cSt; and x_i are the volume percentage of component i.

KV is considered to be the main parameter to assess the impact of fuel on an engine, so Equation 1 was selected to determine the mix ratio. After mixing, the density, kinematic viscosity and surface tension of the ULSD-WOB mixture, at a constant temperature of 30°C, were tested and controlled against ASTM D1298, ASTM D 445 and ASTM D97 standards. A glass hydrometer with a range of 0.7 to 1.0 g/ml was used to determine the density, a CANNON tube viscometer with a viscosity range of 2–30 cSt was used to determine kinematic viscosity, and the Du Nouy ring method was used to determine the surface tension. In addition, each measurement was repeated three times to ensure accuracy, and the average value obtained was considered the result. The measurement results for each test were considered to three decimal places. The stability of the ultrasound-assisted emulsion was also tested. During testing, this stability and the ultrasonic volume of the ULSD-WOB emulsions were also considered, at 2500 rpm and 15 minute separator operation time. The stability of the ULSD-WOB emulsion phase (SEP) was calculated as follows:

$$SEP = \frac{\text{V\_after}}{\text{V\_before}} (\%) \qquad (2)$$

V_after: Emulsion volume after centrifugal treatment, ml
V_before: Total sample volume before centrifugal treatment, ml

2.3. Experimental Setup

The mixing method with the assistance of ultrasound is shown in Figure 1. An ultrasound horn type device was employed. The system emitted an ultrasound frequency of 28 kHz, while the input power of the ultrasound was 100W. The emulsification chamber based on ultrasound was a cylindrical vessel 100 mm in diameter. The mixture of ULSD-WOB was kept at 30°C±1. The height of the ULSD-WOB reaction mixture in the vessel was 100mm, corresponding to around 1.5 liters in volume. The ULSD and WOB were kept in separate tanks and supplied to the emulsification chamber through a pump. The fuel volume was predetermined for each test and was tested by a flowmeter. After mixing, the ULSD-WOB mixture was fed to the storage tank. The properties of the ULSD-WOB mixture and the spray characteristics were then tested. A diagram of the spray characteristic test is shown in Figure 2.

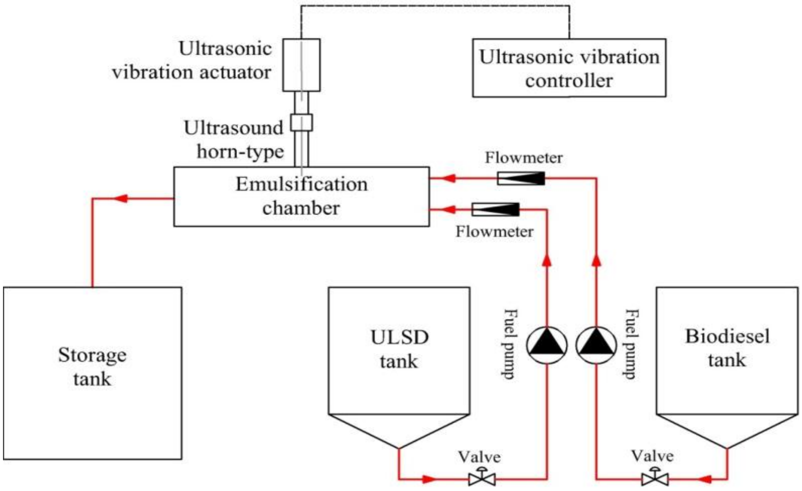

Figure 1 Diagram of the ULSD-WOB mixing based on ultrasound

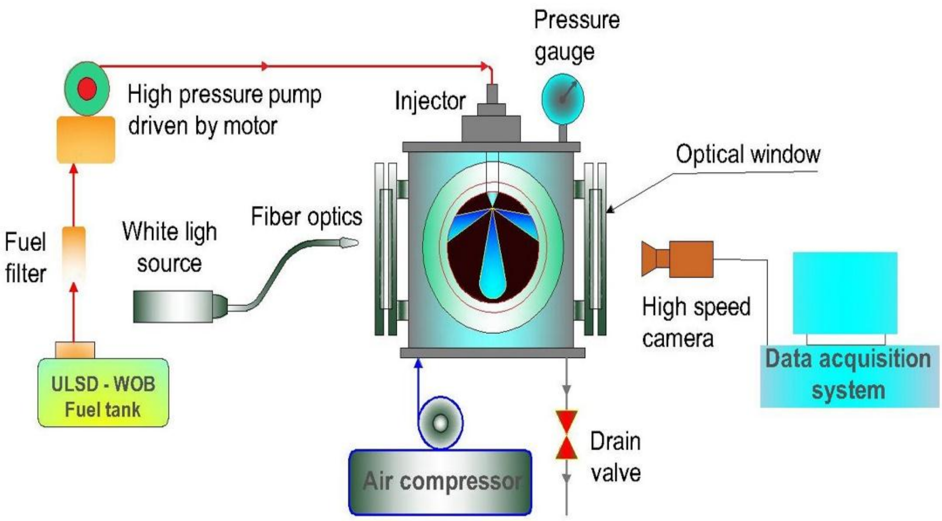

Figure 2 Schematic of the experimental setup for the ULSD-WOB spray characteristics

With reference to Figure 2, the injector used was a simple mechanical fuel type with 200 bar delivery valve opening pressure. The injector was connected to the fuel high-pressure pump, driven by a motor through a high-pressure line. The ULSD-WOB fuel was delivered to the mechanical jerk pump from the ULSD-WOB tank. A high-speed camera with a 120 fps (frames per second) shutter speed and 18-megapixel resolution was located orthogonally to the spray direction to capture the spray images.

3. RESULTS AND DISCUSSION

3.1. Selection of Mixing Rate for ULSD and WOB

The volume percentage of ULSD and WOB were calculated on the basis of Equation 1. The values obtained for the kinematic viscosity of the ULSD-WOB mixture are given in Table 2.

Table 2 Calculation of KV for the ULSD-WOB mixture based on Equation 1 at 30°C

Fuel type	Biodiesel fraction (%)	ULSD fraction (%)	Kinematic viscosity, cSt
ULSD-WOB	5	95	2.15
	10	90	2.39
	15	85	2.64
	20	80	2.88
	25	75	3.13
	30	70	3.37
	35	65	3.62
	40	60	3.86

It can be seen clearly from Table 2 that the KV of the ULSD-WOB mixture with 65% of ULSD and 35% of WOB was 3.62 cSt, compared to 3.60 cSt for the KV of DF at 30°C. This KV of the ULSD-WOB mixture was still 0.6% higher than that of DF. However, the error was lower than 5%, so the mixing rate of the ULSD-WOB mixture was therefore considered to be the most suitable value. The mixture ratio of 65%:35% for ULSD and WOB was selected to conduct the following experiments. In addition, the results obtained in this study were found to be similar to those of Imazu & Kojima (2013) and Li et al. (2010).

3.2. Influence of Ultrasound-horn Position on the Stability of the ULSD-WOB Emulsion

The influence of the position of the ultrasound horn tip on the ULSD-WOB emulsion stability for a prepared mixture of 35% WOB and 65% ULSD after 10 minutes of ultrasonic treatment is shown in Figure 3.

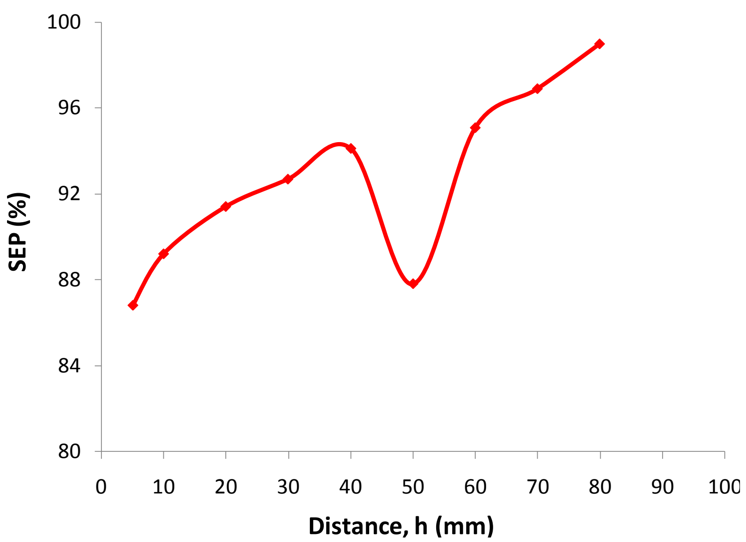

Figure 3 Relationship between SEP (%) and distance h (mm)

The relationship between the distance from the ultrasonic horn tip to the bottom of the emulsification chamber h (mm), and the stability level of the ULSD-WOB emulsion produced, can be clearly observed in Figure 3. The lowest stability level of the ULSD-WOB emulsion was only 86.8% when h = 5 mm, while the highest level was 99%, with the farthest distance h = 80 mm. The results obtained may be explained by the fact that the short distance (h = 5-40 mm) was suitable for the initial disturbance due to the immiscible ULSD and WOB. However, the stability level tended to decrease at around 50 mm distance (h). There may have been a steric obstruction due to the significant immersion of the ultrasound horn in the ULSD-WOB solution. It can be deduced that the cavitation mechanism generated bubbles of ULSD and WOB, and that the mixing of the components produced by the broken bubbles led to the homogeneity of two different types of fuel, which increased the stability of the mixture. On the contrary, the broken bubbles of the homogeneous components from the ULSD-WOB emulsion resulted in a reduction in the stability level, resulting in a breaking of the phase of ULSD-WOB emulsion, which can explain the reduction in the stability level of the ULSD-WOB emulsion at around a distance (h) of 50 mm. Moreover, the ultrasonication-produced acoustic streaming through the horn tip from a distance of 80 mm caused smooth convection currents in the ULSD-WOB solution. The above-mentioned convection currents probably played an important part in the insufficient agitation, leading to the efficient formation of the ULSD-WOB emulsion, as well as its stability level. Similar results were also obtained by Imazu & Kojima (2013) and Navickas et al. (2013).

3.3. Properties of the ULSD-WOB Emulsion

After 10 minutes of ultrasonic treatment, the ULSD-WOB emulsion properties were determined and measured by the measuring devices. The results of the three ULSD-WOB emulsion properties of density, kinematic viscosity and surface tension are given in Table 3. However, the remaining key parameters, the lower heating value (LHV) and cetane number (CN) related to the combustion process of ULSD-WOB emulsion, are predictable because the CN of WOB is higher than that of ULSD and DF (Table 1). Meanwhile, the LHV of WOB is insignificantly lower than that of ULSD and DF.

Table 3 Properties of ULSD-WOB emulsion after ultrasound treatment

Property	Unit	ULSD-WOB emulsion	WOB	ULSD	DF
Density, ρ	kg/m^3	853	880	832	852
Kinematic viscosity, KV	cSt	3.64	7.2	1.9	3.6
Surface tension, ST	N/m	25.4	26.5	24.4	25.2

From Table 3, the higher values of the three ULSD-WOB emulsion properties compared to DF can be seen. Kinematic viscosity, density and surface tension levels were 1.2%, 0.12% and 0.8% higher than those of DF respectively. However, these values still satisfy the requirements of fuel for use in diesel engines. Therefore, the results achieved based on the mixing rate of 65%:35% of ULSD and WOB were considered to be the optimal ones, and they were also the same as those obtained in studies of Korkut & Bayramoglu (2014), and Lin and Chen (2008). The kinematic viscosity error between the given value in Table 2 (3.62 cSt) and the experimental result (3.64 cSt) is very small, equal to 0.55%. Furthermore, the SEP and KV of the ULSD-WOB emulsion as a function of the ultrasound treatment time at a distance (h) of 80 mm are plotted in Figure 4.

The trend in the changes in the SEP and ULSD-WOB emulsion can be clearly seen in Figure 4. After the first 10 minutes, SEP had changed insignificantly and it seemed to be a constant. A similar KV result also occurred after 10 minutes of ultrasound treatment. However, the trends of SEP and KV seemed to occur in opposite directions; although their values showed an asymptote to the stable ones, the SEP value was near to 100% and the KV value equal to 3.64 cSt.

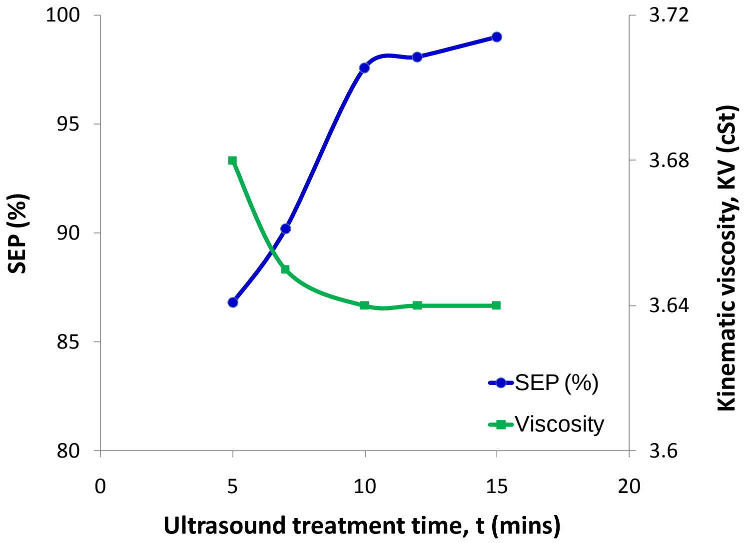

Figure 4 Changes in SEP (%) and kinematic viscosity (KV) of the ULSD-WOB emulsion with ultrasound treatment time (t) at h = 80mm

3.4. Influence of ULSD-WOB Emulsion Properties on Spray Characteristics

Besides the requirements of fuel such as CN and LHV, fuel spray characteristics also play a very important role in the combustion process and emission characteristics of diesel engines. The quality and homogeneity of the air-fuel mixture in the engine cylinder depend on the size of the fuel droplets after spraying. The smaller the fuel droplet size, the greater the total heated area is, and the faster the evaporation rate (Hoang & Le, 2019b). However, fuel droplets greatly depend on the type of fuel, and homogeneous spraying is the key factor in forming a homogeneous mixture. Several indicators characterize fuel spray characteristics and fuel injection quality, with spray penetration and the cone angle of the fuel spray structure being considered the main parameter, which is greatly affected by the three properties of the fuel previously presented. A large spray penetration and cone angle demonstrate the large size of the fuel droplets. The aim of determining the spray characteristics is to evaluate the similarity and compatibility of the spray structure of the generated ULSD-WOB emulsion in comparison to DF. The spray characteristics of the ULSD-WOB emulsion compared to ULSD, DF and WOB are shown in Figure 5.

An improvement in spray penetration and the cone angle of the ULSD-WOB emulsion in comparison to WOB can be seen clearly in Figure 5.. At room temperature, the spray penetration of ULSD (Figure 5a) was 186 mm, which is much lower than that of DF (Figure 5b) and WOB (Figure 5c) because of its low KV. The effect of the low KV of ULSD on the wear and erosion of injectors in diesel engines has been reported in the literature (Ushakov et al., 2013). In order to overcome this ULSD disadvantage (low KV), the use of a chiller is compulsory in marine diesel engines, but the cost of this is very high. Compared to ULSD, the high KV of WOB was also considered as a big disadvantage, resulting in difficulties in achieving fast evaporation and mixing to produce a homogeneous mixture in the combustion chamber. The spray penetration for WOB increased by 7 mm compared to DF, and 26 mm compared to ULSD. On the contrary, the cone angle for WOB was 2o smaller than that of DF. After the emulsification by ultrasound, the ULSD-WOB emulsion showed a similar spray penetration and cone angle to DF. The spray penetration for the ULSD-WOB emulsion (Figure 5d) was only 1 mm higher than that of DF, and its cone angle was equal to DF. The results obtained demonstrate the improvement in the ULSD and WOB properties based on the mixing method assisted by ultrasound. It is clear that the ULSD-WOB emulsion generated meets the current requirements related to fuel standards for diesel engines. Furthermore, easy evaporation of the ULSD-WOB emulsion compared to WOB can be seen in Figure 5.

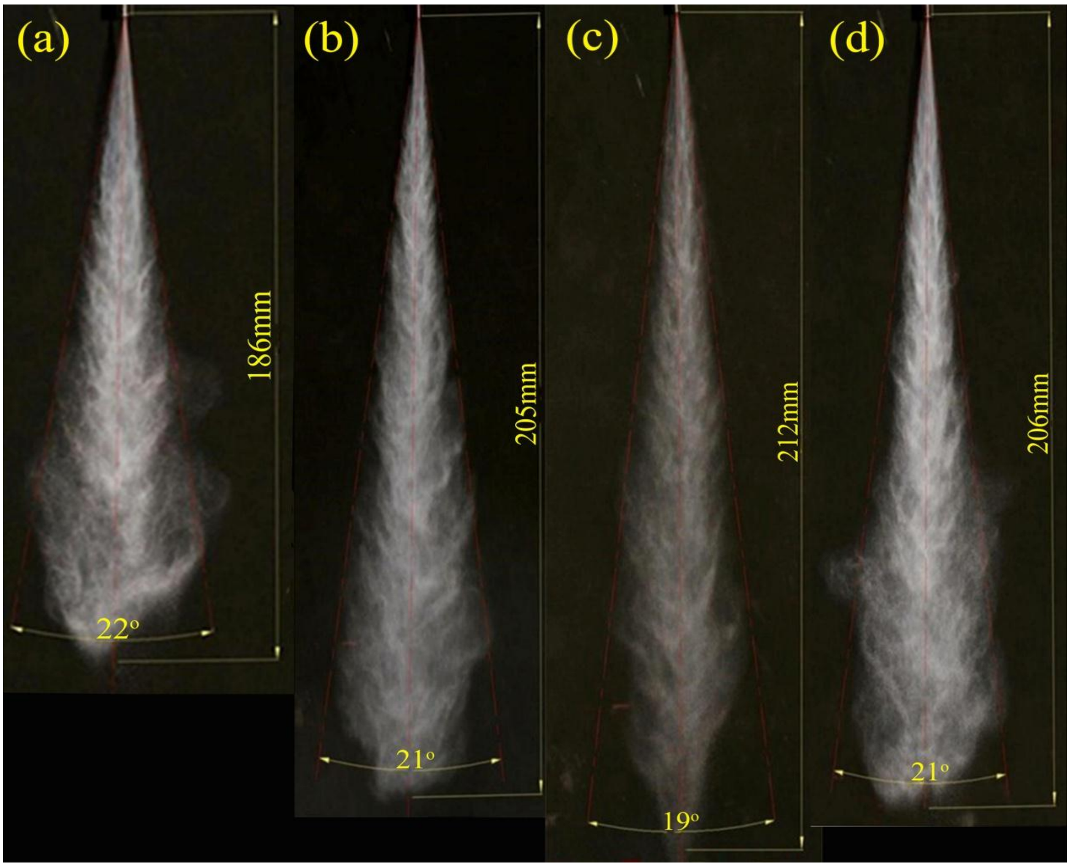

Figure 5 Spray characteristics of the four types of test fuel at room temperature

4. CONCLUSION

A mixing method for two immiscible fuel types with a large difference in kinematic viscosity such as ULSD and WOB with ultrasound treatment has been suggested in this experimental investigation. The mixing ratio of ULSD to WOB was 65%:35%, and an optimal value of 80 mm was found for the distance from the horn tip to the bottom of the emulsification chamber, along with an ultrasound frequency of 28 kHz and ultrasound power of 100 W. After 15 minutes of ultrasound treatment, the stability of the ULSD-WOB emulsion reached its highest value of 99%. In addition, three properties of the ULSD-WOB emulsion, viscosity, density and surface tension, were equal to those of DF. The spray characteristics of the ULSD-WOB emulsion-based fuel, including penetration and cone angle, were improved compared to ULSD and WOB. The very small difference between the spray characteristics of the ULSD-WOB emulsion-based fuel and DF was around 0.5% for penetration. As a result, the mixture of 65% ULSD and 35% WOB after ultrasound treatment is similar to DF in relation to the three properties and spray characteristics. It is worth mentioning that the very low sulphur content and the presence of oxygen in the ULSD-WOB emulsion are its main advantages in its use for diesel engines and contributioin towards sustainable development.

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