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Influences of Heating Temperatures on Physical Properties, Spray Characteristics of Bio-oils and Fuel Supply System of a Conventional Diesel Engine

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***Abstract*—Alternative fuels need to satisfy the strict requirements of the use for diesel engines aiming at enhancing the performance and reducing pollutant emissions. The use of straight bio-oils for diesel engines entails improving their disadvantages such as high density, high surface tension and kinematic viscosity (tri-physical parameters). There have been some as-used methods for reduction of the above-mentioned negative effects related to straight bio-oil disadvantage, however, the adequately-heating method may be considered as a simple one helping the physical parameters of straight bio-oils to reach stable and highly-confident values which are close to those of traditional diesel fuel. As a consequence, the spray and atomization, combustion, performance, and emissions of diesel engines fueled with preheated bio-oils are improved. In this work, a study of the dependence of the density, surface tension and kinematic viscosity of coconut oil (a type of bio-oils) on temperatures (from 40-110^{o}C) within a wide variety are conducted. In the first stage, the influence study of temperature on tri-physical parameters is carried out on the basis of experimental correlation and as-described mathematical equation. In the second stage, the influence study of tri-physical parameters on spray and atomization parameters including penetration length (L_b) and Sauter mean diameter (SMD), and the influence of tri-physical parameters on fuel supply system are investigated. The optimal range of temperature for the as-used bio-oils is found after analyzing and evaluating the obtained results regarding the physical properties and spray characteristics, as well as compared with those of diesel fuel. The confident level over 95% from the regression correlation equation between the above-mentioned tri-physical parameters and temperature is presented. Additionally, the measured spray parameters, the calculated values of frictional head loss and fuel flow rate are thoroughly reported.**

***Keywords*—bio-oils; tri-physical parameters; spray parameters; fuel supply system; heating temperature.**

I. INTRODUCTION

Due to high durability and featured advantage of the performance, diesel engines have been being widely used in the world, especially in the fields such as transportation, construction, forestry agriculture, fishery, and stationary generators [1][2]. As reported in the literature, diesel engines could use some various fuel types including fossil-based fuels (diesel fuel, DME, DEE, LPN, CNG) or alternative fuels (HVO, biodiesel, vegetable oils), or hybrid fuels [3][4].

In recent years, challenges related to the increase of energy demand, global warming, environmental pollution, fossil fuel depletion cause urgent concerns of researchers, policymakers aiming at finding the solutions for the above-mentioned problems [5][6]. Thus, development of renewable and alternative fuels with environmentally-friendly characteristics is considered as a key strategy and task [7][8]. One of the renewable fuel types are bio-oils which include vegetable oils and animal fats [9]. However, the use of vegetable oils, especially nonedible-vegetable oils, is more common because there is not a conflict with the food chain. Using vegetable oils as fuel is not new and dates back to the end of the 19th century with the inventor of the diesel engine. In the 1900s, at the Universal Exhibition in Paris, the OTTO company exhibited a small engine running exclusively on groundnut oil without any modification [10]. During World War II, vegetable oils were used to power diesel engines in isolated areas. Many researchers from different countries have been still investigating the use of different types of vegetable oils for diesel engines [11][12]. For example, soybean oil was used in the USA, while rapeseed oil and sunflower oil were using in Europe, palm and coconut oil were using Southeast Asia, and cottonseed oil and Jatropha curcas oil were using West Africa. Most studies indicated the attractive options for vegetable oils on a small scale due to environmental benefits and simple processing [13]. Generally, pure vegetable oils showed a lower energy and fewer chemicals consumption in comparison with the trans-esterification stage and they were converted into biodiesel [14].

Some similarities between traditional diesel fuel and vegetable oils regarding the heating value and cetane number or the use of vegetable oils for unmodified diesel engines were reported. An increase in unburned hydrocarbon (UHC) and carbon monoxide (CO) [15], a decrease of particulate matter (PM), nitrogen oxides (NOx) and CO_2 emission were observed [16][17]. However, an accepted fact related to higher density, kinematic viscosity and surface tension than those of diesel fuel resulting in the difficulties in spray process such as lower fuel atomization and fuel speed, lower cone angle, higher Sauter mean diameter, higher penetration length was indicated [18]. Besides the dependence of fuel atomization on the injector geometry, the atomization effectiveness is strongly affected by tri-physical properties of fuels which showed profound influences on the liquid-fuel flow in the fuel supply system [19]. In addition, low atomization and incomplete combustion of diesel engines running on pure vegetable oils leading to low power, coking and deposit in the injector and combustion chamber were also presented [20].

As reported in the literature, there were many studies concentrate on the reduction of tri-physical parameters of vegetable oils by heating method. In the earliest study of Murayama et al. [21], they have used preheated rapeseed oil for a direct injection diesel engine, as a result, preheating temperature to 200^{o}C was found as the suitable temperature in their study to achieve efficient combustion. In another study of Agarwal et al. [22], Jatropha oil that was preheated to between 90^{o}C and 100^{o}C aiming at reducing tri-physical properties within a close range to diesel was used for a diesel engine, an optimal fuel injection pressure was found to be unchanged. Hoang [23] has designed and fabricated a kit for utilizing the exhaust gas energy of a diesel engine to preheat coconut oil up to 110^{o}C, an improvement of engine power and emission parameters was reported. Moreover, some available heat sources in diesel engines may be utilized to raise the temperature of vegetable oils in the viscosity reduction. Normally, some kits used for purposes of increase in temperature are the cooling-water circuit and exhaust gas which heat vegetable oils up to around 70^{o}C and 80^{o}C.

It is clearly seen a core relationship between key physical properties of bio-oils and temperatures such as specific density, surface tension and kinematic viscosity based on the above-mentioned equations. In addition, the influence of tri-parameters (specific density, surface tension and kinematic viscosity) of bio-oils on spray and atomization, break-up mechanism, combustion process, performance, emissions of diesel engines as well as the influence of the dynamic characteristic of the liquid fuel flow on fuel pipes and pumps, and filter were reported. Those showed the importance of evaluation and adjustment of the values of the above tri-parameters to meet the requirements of fuel used for diesel engines. Tri-physical properties of vegetable oils have to be lowered to allow direct use in unmodified diesel engines. This means that the spray and atomization are improved, the injection speed of preheated vegetable oil increases, as well as the effects of preheated vegetable oil are small. If not, the incomplete combustion of vegetable oils and carbonization in the combustion chamber will damage diesel engines. Although physical properties of bio-oils play an important part in the determination and the evaluation of the effectiveness of fuel use, there were a few published research works related to the optimization of heating temperature for bio-oils aiming at improving the spray characteristics as well as the performance and emissions of diesel engines. In this work, the establishment and evaluation of the core relationship between key tri-parameters and temperature and the effects of fuel properties on the spray and atomization, fuel supply system are introduced and developed.

II. Materials and Methods

A. Materials

In this study work, pure coconut oil (CO100), pure jatropha oil (JO100) and pure soybean oil (SO100) were used. The advantages of pure vegetable oils when used as fuel for diesel engines are liquidity, ready availability, renewability, no sulfur and aromatic content, and biodegradability. However, the main disadvantages of pure vegetable oils are higher viscosity, higher surface tension, higher density otherwise lower volatility. The physical and chemical properties of the above-mentioned vegetable oils compared with diesel fuel (DF) are given in Table I.

TABLE I
PROPERTIES OF CO100, JO100, SO100, AND DF AT 30^{o}C

Properties	Unit	CO100	JO100	SO100	DF
Density, ρ	kg/m^3	913	905	910	852
Kinematic viscosity, KV	cSt	32.6	30.2	31.5	3.5
Surface tension, σ	mN/m	31.2	29.8	30.3	25.5

B. Methods

1) The relationship between kinematic viscosity, surface tension, density of vegetable oil and temperature

Density (ρ) of vegetable oil is defined as the ratio of vegetable oil mass and vegetable oil volume under certain condition. The 1st degree linear shown in Eq. (1) for the dependence of ρ on temperatures was proposed by Tat and Garpen [24] based on hydrometer for experimental measurement. On the other hand, another equation was suggested by Rodenbush [25] and shown in Eq. (2):

$$\rho = a + bT \tag{1}$$

$$\rho = \frac{\rho_o}{1+\beta(t_1 - t_o)} \tag{2}$$

Where

ρ_1 ; ρ_o - final density and initial density of vegetable oil, kg/m^3

t_1 ; t_o - final and initial temperature of vegetable oil, ^oC

T - temperature, K

β - volumetric temperature expansion coefficient of vegetable oil, $m^3/m^3\,^oC$

a, b - constants depending on vegetable oil type

Kinematic viscosity (KV) is a parameter characterizing the resistance to the flow of liquid. The higher the viscosity is, the more unfavorable the usage is, because it reduces the dispersing possibility the fuel injection into the combustion chamber as well as increases the ability of the sedimentation formation in the equipment and fuel supply system. Viscosity is inversely proportional to the temperature. The reason causing high viscosity is thought due to high molecular, long carbon-chains of unsaturated fatty acids. The viscosity of the vegetable oil is around 10 to 17 time higher than that of diesel fuel, it is thus necessary to reduce the viscosity of vegetable oil when it is considered as alternative fuel for diesel engines. Methods have been being used to improve the disadvantages of vegetable oil such as blending or heating method, the conversion of vegetable oil into biodiesel, or the usage of additives. Heating is one of the simplest methods that may be applied to agricultural or generator diesel engines. There were some introduced equations to evaluate the effect of temperature on the kinematic viscosity of the vegetable oil. They are presented in Eq. (3) to Eq. (5) [26].

$$\log \mu = A + \frac{B}{T} \qquad (3)$$

$$\ln KV = A.T^2 + BT + C \qquad (4)$$

$$KV(T) = KV_0 \exp(-bT) \qquad (5)$$

Where:
KV - kinematic viscosity, cSt
A, B, C, KV_o, b - coefficients
T - temperature, K

Surface tension (σ) is defined as the force exerted in the plane of the surface per unit length. Therefore, while the surface tension of the fuel is high, the injection and atomization will be less, and this affects the quality of the combustion of diesel engines adversely. Surface tension is proportional to viscosity and inversely proportional to temperature. Some models were used to determine the value of surface tension in the relationship of the temperature, such as Eq.(6) and Eq.(7) [27]:

$$\sigma = \left[P(\rho_l - \rho_v\right]^4 \qquad (6)$$

$$\sigma = A + B.T + C.T^2 + D.T^3 \qquad (7)$$

Where:

ρ_l and ρ_v - density of liquid and vapor, kg/m^3

$P = P_0(1-T_r)^{0,37}.T_r.\exp(A/T_r + BT_r^9)$

$P_0 = C[D - E(R^*/T_b^2)].T_c^{13/12}.p_c^{-5/6}$

$R^* = R_m/R_{m-ref}$

A = 0,30066; B = 0,86442; C = 39,6431

D = 0.22217; E = $2,91042.10^3$

$T_r = T/T_c$

T, T_c - heating and critical temperature, K

p_c - critical pressure, N/m^2

P_o - a temperature function which depends on the vegetable oil molar structure

R_m - vegetable oil molar refraction

R_{m-ref} - molar refraction of the reference fluid

T_b - the reduced normal boiling point, K

A, B, C, D - empirical constants, depending on the type of vegetable oil.

2) The relationship between kinematic viscosity, surface tension, density, and spray characteristics

In the combustion chamber, the atomization process affects the fuel-air mixture quality strongly. To evaluate spray and atomization process, three parameters including the spray penetration length (L_b), cone angle (θ), and Sauter mean diameter (SMD) are used. The spray penetration length (L_b) is a very important characteristic to define the behavior of the spray in the combustion chamber. Spray penetration length (L_b) is proposed by Lefebvre et al. [28] as followed:

$$L_b = 7.D.\left(1 + 0.4\frac{r}{D}\right).\left(\frac{p_g}{\rho_l u^2}\right)^{0.05}.\left(\frac{L}{D}\right)^{0.13}.\left(\frac{\rho_l}{\rho_g}\right)^{0.5} \qquad (8)$$

The droplets usually do not exist at a uniform drop size throughout the spray due to the variety of atomization processes, droplet interactions and their heterogeneous nature. The Sauter mean diameter (SMD) of a spray presents the droplet diameter (d) that has the same volume/surface ratio as that of the total spray. It indicates the quality of the atomization process. The Sauter mean diameter (SMD) is also the most useful value for determining the rate of evaporation. Hiroyasu [29] showed an empirical equation for SMD/d:

$$\frac{SMD}{d} = 0.38.\mathrm{Re}_l^{0.25} We_l^{-0.32} (\frac{\mu_l}{\mu_g})^{0.37} \left(\frac{\rho_l}{\rho_g}\right)^{-0.47} \qquad (9)$$

The cone angle is defined as the angle formed by two straight lines that start from the exit orifice of the nozzle and tangent to the spray outline in a determined distance. Martínez et al. [30] proposed an empirical equation as follows:

$$\tan(\frac{\Phi}{2}) = 0.13.\left(1 + \frac{\rho_l}{\rho_g}\right) \qquad (10)$$

Where:

$We_l = \dfrac{u^2 D}{\sigma_l}\rho_l$ - Weber number

$Re_l = \dfrac{uD}{\mu_l}\rho_l$ - Reynolds number

ρ_l, ρ_g - density of the fuel and the gas, kg/m^3
μ_l, μ_g - fuel and gas dynamic viscosity, N.s/m^2
D - nozzle hole diameter, mm
σ_l - fuel surface tension, N/m.

3) *Kinematic viscosity, surface tension and density measurement*

The ASTM D1298 standard was used to measure the density. A glass hydrometer with a specific gravity range of 0.7 to 1.0 g/cm^3 with an accuracy of three decimal places and the range of temperature between 40°C to 110°C was used. The test was repeated twice and the average value was taken.

The kinematic viscosity was determined by measuring the time taken for a known volume of vegetable oils flowing under gravity to pass through a calibrated glass capillary viscometer tube based on the ASTM D445 standard and kinematic viscosity range from 2 to 30cSt. The experimental data satisfies the ASTM D445 standard, which requires the tests to be done two times with an accuracy of 0.02cSt. The tests were repeated two times and the average value was taken as the representative value.

To measure surface tension, there were some of the methods such as Du Nouy ring, Whilhelmy plate, Spinning drop, Pendant drop, Bubble pressure, Stalagmometric, Sessile drop. This paper used Du Nouy ring method with a tension meter based on the ASTM D971 standard.

4) *Measurement of the influence of fuel properties on fuel supply system*

Normally, two key factors such as the friction head loss (H_f) and flow rate (FR) are used to aim at determining the influences of the viscous force of liquid fuels on its motion ability from the pump network to filter through the pipe/line. Additionally, SMD, L_b and Φ play an important role in the evaluation of fuel spray parameters. Nevertheless, it is very difficult to evaluate the effect of fuel properties on the fuel supply system.

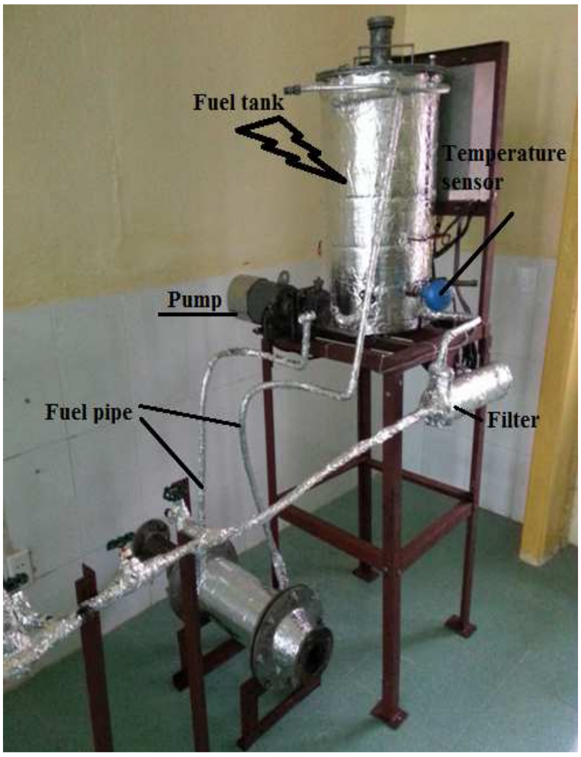

Fig. 1. A heating fuel supply system

Therefore, a highly-exact mathematical model with small errors should be used to predict the above-mentioned parameters according to the different conditions in the operation process of diesel engines. The heating fuel supply system, which was fabricated by the author aiming to evaluate the effect of preheated vegetable oils on the fuel supply system, was shown in Fig.1. The technical parameters of the as-fabricated fuel supply system were given in Table II.

TABLE II
PROPERTIES OF CO100, JO100, SO100, AND DF AT 30°C

Para-eters	Fuel pipe length, L	Fuel pipe diameter, d_p	Pump head, P	Pump flow rate, H	Volume of fuel tank, V
Unit	mm	mm	kG/cm^2	l/h	l
Value	2000	25	2	73.5	50

Fuel flow rate (FR) was determined by Eq. (11) which presented the dependence of FR on time (t) and of KV [28].

$$FR = \frac{C}{KV.t} \tag{11}$$

The frictional head loss (H_f) value might be calculated by the following equation [31]:

$$H_f = 2.4384.F_f.\frac{L}{d_p}.\frac{P_j - P_c}{\rho_l.g} \tag{12}$$

Where:
t - time, s
C - constant depending on filtration property
F_f - dimension-less friction factor, $F_f = \frac{0.0396}{\mathrm{Re}^{0.25}}$ (13)

P_j - injection pressure, bar
P_c - pressure in the cylinder, bar
g - gravitational acceleration, m/s^2

III. RESULTS AND DISCUSSION

A. *The dependence of kinematic viscosity, surface tension, density of vegetable oils on the heating temperature*

The prediction of kinematic viscosity (KV), surface tension (σ), density (ρ) of vegetable oils aims to determine the proper heating temperature for the direct-use strategy for diesel engines because proper heating-temperatures help the atomization well and evaporation fast to form the homogeneous and ignitable mixture. The dependence of ρ on the heating temperature of the as-used vegetable oils including CO100, JO100, and SO100 is plotted in Fig. 2.

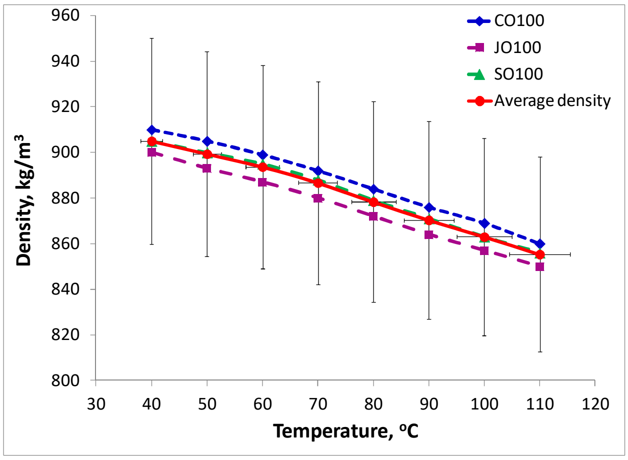

Fig. 2. The relationship between density and heating temperature

It is clearly seen from Fig.2 that ρ of vegetable oils is inversely proportional to heating temperatures. Achieved results from Fig. 2 showed that the densities of three types of vegetable oils are much higher than that of diesel fuel. However, these values tended to reduce along with the increase of temperatures. Around 110°C of heating temperature, the densities of as-used vegetable oils are ensured to be below 860 kg/m^3, corresponding to European standard EN 14214:2008 [32]. In fact, due to different requirements depending on engine types or fuel supply system types and configurations, combined heat and power (CHP)-based engines may use injected fuels under lower temperatures [33]. The average density of three used vegetable oils is shown with red line in Fig. 2, from this red line first-degree equation with $R^2 = 0.9961$ is presented in Eq. (14).

$$\rho = -0.7234\,T + 935.71 \tag{14}$$

The obtained density values calculated by Eq. (14) and experimentally measured are compared and given in Table III.

TABLE III
THE COMPARISON OF EMPIRICAL RESULTS AND CALCULATED RESULTS

Temperature,°C	ρ_CO100	ρ_JO100	ρ_SO100	ρ_1	Δ_1	Δ_2	Δ_3
40	910	900	905	906.774	0.003545	0.007527	0.00196
50	905	893	900	899.540	0.006033	0.007324	0.00051
60	899	887	895	892.306	0.007446	0.005982	0.00301
70	892	880	888	885.072	0.007767	0.005764	0.00330
80	884	872	879	877.838	0.006971	0.006695	0.00132
90	876	864	871	870.604	0.006160	0.007644	0.00045
100	869	857	863	856.136	0.014803	0.001010	0.00795
110	861	850	856	856.136	0.005649	0.007219	0.00016

From Table II, it can be clearly seen that the density values calculated by Eq. (14) (ρ_1) in comparison with the measured density values by experiment. The errors including Δ_1 (between ρ_CO100 and ρ_1), Δ_2 (between ρ_JO100 and ρ_1), and Δ_3 (between ρ_SO100 and ρ_1) show very small values. The maximal error is 1.4% at 100°C of heating temperature and between ρ_CO100 and ρ_1, however, this error value is lower 5% and it is highly accepted. The as-presented results from Table II and Fig.2 indicate the liner of the density-temperature of as-used vegetable oils clearly that, the density of either diesel fuel or pure vegetable oils can be adjusted on the basis of a straight-line mean, leading to a significant statistics with high determination coefficients (> 98% in all cases).

The kinematic viscosity (KV) of each fuel is considered as the important factor evaluating the atomization level as well as the fast vaporization when fuel is injected into the cylinder. The KVs of three types of as-used vegetable oils, which were measured from 40°C-110°C by experimental method, are shown in Fig. 3 and Table IV.

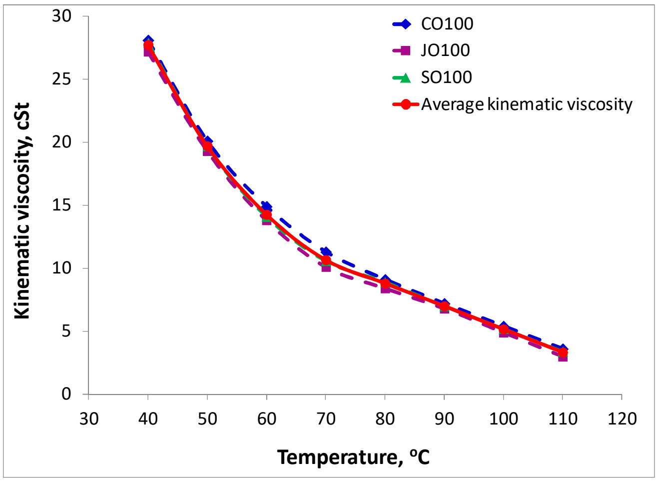

Fig. 3. The relationship between kinematic viscosity and heating temperature

TABLE IV
KV VALUES OF VEGETABLE OILS DEPENDING ON TEMPERATURES

Vegetable oil types	Temperature, °C	A	B	C	R^2	KV_1, cSt	KV_2, cSt	KV_3, cSt	Δ_4, %	Δ_5, %
CO100	40	0.0047	-1.0280	60.609	0.9886	28.1	27.009	26.889	0.0388	0.0431
	50					20.1	20.959	20.322	0.0427	0.0110
	60					14.9	15.849	15.359	0.0637	0.0308
	70					11.3	11.679	11.608	0.0335	0.0273
	80					9.1	8.449	8.773	0.0715	0.0359
	90					7.2	6.159	6.631	0.1446	0.0791
	100					5.4	4.809	5.011	0.1094	0.0720
	110					3.6	4.399	3.788	0.2219	0.0521
JO100	40	0.0048	-1.0403	59.948	0.9842	27.2	26.016	26.512	0.0435	0.0253
	50					19.3	19.933	19.838	0.0328	0.0279
	60					13.8	14.810	14.844	0.0732	0.0756
	70					10.1	10.647	11.107	0.0542	0.0997
	80					8.4	7.444	8.311	0.1138	0.0106
	90					6.8	5.201	6.219	0.2351	0.0855
	100					4.9	3.918	4.653	0.2004	0.0503

	110					3.2	3.595	3.482	0.1234	0.0881
SO100	40	0.0050	-1.0607	61.196	0.9838	27.9	26.768	26.667	0.0406	0.0442
	50					19.7	20.661	20.154	0.0488	0.0231
	60					14.1	15.554	15.232	0.1031	0.0803
	70					10.6	11.447	11.512	0.0799	0.0861
	80					8.9	8.340	8.701	0.0629	0.0224
	90					7.0	6.233	6.576	0.1096	0.0606
	100					5.2	5.126	4.970	0.0142	0.0442
	110					3.4	5.019	3.756	0.3942	0.0434

It is clearly seen from Fig. 3 that there is a decrease of KV of vegetable oils when increasing the heating temperature. Based on the practical results, a second-degree equation such as Eq. (4) or exponential equation such as Eq. (5) is suggested. For a second-degree equation such as Eq. (4), the empirical coefficients including A, B and C, and value R^2 for each vegetable oil type are given in Table III. A regression correlation between KV and temperature based on the second-degree equation is described by Eq. (15) with R^2 = 0.9836. Besides, a regression correlation between KV and temperature according to the exponential equation such as Eq. (16) with R^2 = 0.9938 is also proposed as followed:

$$KV = 0.0049T^2 - 1.0519T + 60.71 \qquad (15)$$

$$KV = 82.485\exp(-0.028T) \qquad (16)$$

The obtained KVs of the vegetable oils in the relationship with heating temperatures ranging of 40°C to 110°C through empirical method is from 3.20 cSt to 28.10 cSt, are from 3.595 cSt to 27.009 cSt based on Eq. (15), and from 3.482 cSt to 26.889 cSt based on Eq. (16). In addition, the absolute error (Δ_4) between empirically-measured KV_1 and KV_2 achieved from Eq. (15), and the absolute error (Δ_5) between empirically-measured KV_1 and KV_3 achieved from Eq. (16) are also reported in Table IV. The maximal absolute error for Δ_4 is 39.42% in, and this maximal value for Δ_5 is 9.97%. This absolute error shows that a second-degree equation from Eq. (15) for estimation of regression correlation between KV and temperature is unacceptable due to Δ_4 > 10%. On the contrary, the value of Δ_5 is shown lower than 10%, and Eq. (16) may be thus used to predict the dependence of KV of the vegetable oils on the heating temperature. The relationship between surface tension and the heating temperature is shown in Fig. 4.

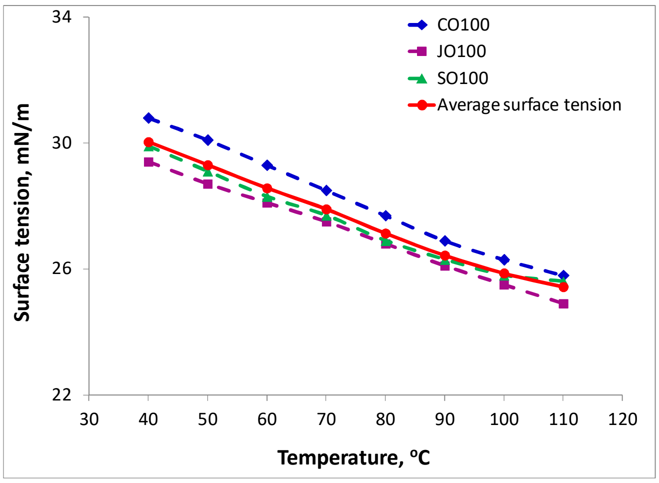

Fig. 4. The relationship between surface tension and heating temperature

From Fig. 4, it can be seen that the regression correlation between surface tension and heating temperature can be described by a first-degree equation with R^2 = 0.9954. This correlation is presented by Eq. (17):

$$\sigma = -0.0637T + 32.631 \qquad (17)$$

Based on Eq. (17), surface tension is calculated and compared with the empirical values, the absolute error between the two above-mentioned values is 6.52%. With this error, Eq. (17) is highly acceptable to estimate the relationship between surface tension and heating temperature. Regarding the dependence of KV and surface tension on density, they can be seen in Fig. 5 and Fig. 6.

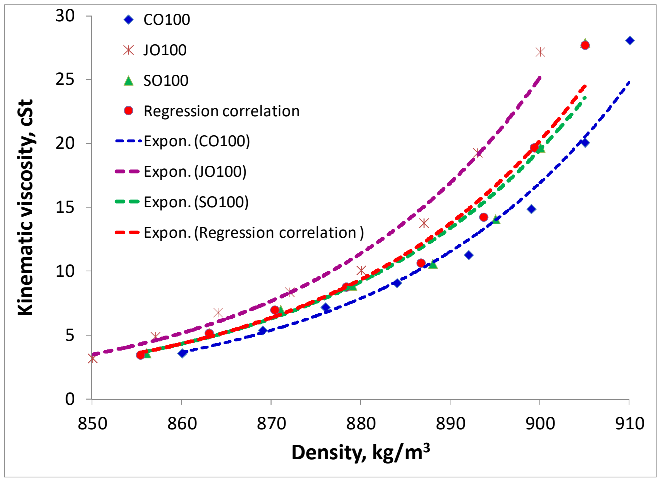

Fig. 5. The relationship between KV and density of three studied vegetable oil types

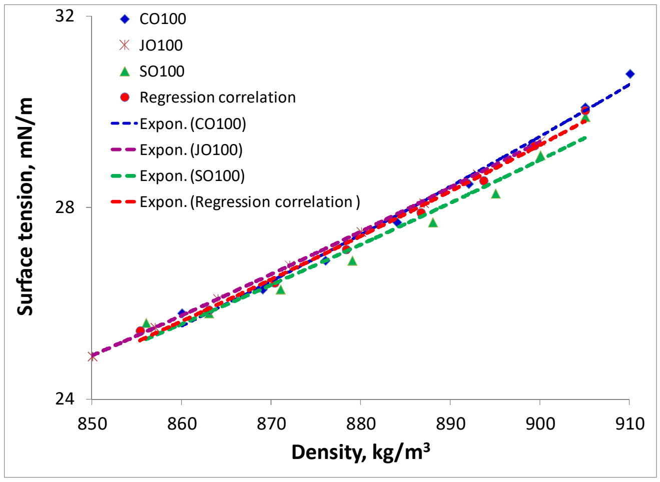

Fig. 6. The relationship between surface tension and density of three studied vegetable oil type

To describe the KV and surface tension of vegetable oils as a function of their densities, a regression correlation of the above-mentioned relationship is conducted and is shown in Fig. 5 and Fig. 6. After linearizing the points in Fig. 5 and Fig. 6, the correlation equation for the dependence of KV on density (ρ) with R^2 = 0.9924 of confidence level, and the correlation equation for the dependence of surface tension (σ) on density (ρ) with R^2 = 0.9915 of confidence level are given in Eq. (18) and Eq. (19), respectively.

$$KV = 2E(-14)\exp(0.0385\rho) \tag{18}$$

$$\sigma = 0.0925\rho - 53.934 \tag{19}$$

Obtained results from Eq. (18) and Eq. (19) indicate a prediction of the vegetable oil KV and surface tension with high confidence, these correlations are same as past studies [34][35].

B. Influence of vegetable oil physical properties on the fuel supply system

As reported in the literature, the fuel supply system (FSS) of engines plays an important role in providing the measure fuel volume/mass, which is accordant with the operation modes of engines. In addition, FSS also ensures that each cylinder of the engine is provided with fuel in the correct time as well as fuels must be atomized and dispersed into the combustion chamber aiming at homogeneous mixture before igniting. Moreover, ensuring the engine be provided with fuel to work continuously and smoothly during the designed time is an obligation of FSS. Besides, other functions of FSS such as purifying mechanical impurities and the water, the easy flow of fuel are considered. The above-mentioned requirements and functions of FSS require engines to use fuels, which satisfy the ASTM standards. Obviously, fuels with high KV, surface tension (σ), and high density (ρ) such as vegetable oils will influence the components of FSS in engines, the fuel pump network, and filter are examples. As presented in Section III.B.2, two factors, being the fuel flow rate (FR) and frictional head loss (H_f), are used to evaluate the effects of fuel properties on the FSS. The dependence of FR in the filter of FSS on the time in case of various values of heating temperatures is calculated by Eq. (11) and is plotted in Fig. 7.

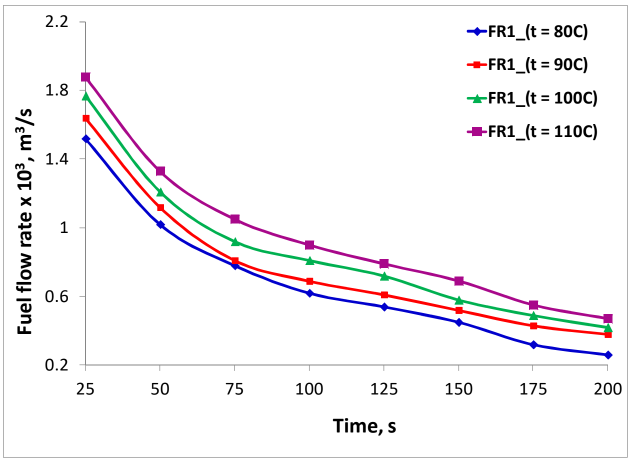

Fig. 7. The dependence of FR in the fuel filter on the time at various heating temperatures

It can be clearly seen the ratio between FR and heating temperatures from Fig. 7, it means that an inverse proportion between FR and fuel physical properties (KV, σ, ρ) is ascertained. Obtained results from Fig. 7 are because the active voidage ratio and the total fuel-volume of filtration in the filter of FSS are known with higher values at starting the period, and this active voidage ratio is always decreased after working, leading to the filtration rate for fuels at a constant value. From Fig. 7, it is evident that the filtration rate for fuels is observed with a nearly-constant value after around 175s. For average results, the FR through the fuel filter in FSS at a heating temperature of 80°C is respectively 11.77%, 25.90%, and 48.27% higher than that of the heating temperature of 90°C, the heating temperature of 100°C, and the heating temperature of 110°C. The calculated results of H_f from Eq. (12) in case of fuel injection pressure Pj = 200 bar and pressure in the cylinder P_c = 40 bar is given in Table V.

TABLE V
FRICTIONAL HEAD LOSS- H_F OF THE FUEL PUMP AT VARIOUS HEATING TEMPERATURES

Heating temperature, °C	**Fuel velocity u, m/s**	**Dimension-less friction factor, F_f**	**Frictional head loss H_f, m**
80	184.86	0.00807	2.712
90	185.63	0.00781	2.604
100	186.40	0.00678	2.297
110	187.19	0.00655	2.238

The results calculated from table V show that H_f values at low heating temperature are also higher than those at high heating temperature, the H_f value at heating temperature of 80°C is respectively 3.98%, 18.06%, and 21.14% higher than that of heating temperature of 90°C, heating temperature of 100°C, and heating temperature of 110°C. Therefore, this may indicate that liquid fuels with lower (KV, σ, ρ) may result in lower flow resistance which is considered as the main cause leading to a decrease of H_f and an increase in FR of liquid fuels while they pass the fuel filter in FSS. Also, the similar results are found in other studies [36].

C. Influence of vegetable oil physical properties on spray characteristics

In fact, fuel types with the large molecular or high long-chain carbon due to triglyceride components contained in vegetable oils may be considered as the main cause leading to higher KV and surface tension (σ), and higher density (ρ) as well as lower volatility in comparison with traditional diesel fuels. Clearly-seen disadvantages of vegetable oils result in poor spray and atomization along with large fuel-droplet sizes (d), small cone angle (θ), and high penetration (L_b). It is evident that the emission characteristics and thermal efficiency of diesel engines running on vegetable oils are strongly affected by atomization and spray, mixing, and complete combustion in the combustion chamber. The study of Hoang et al. [37] has showed that the fuel spray composed of large fuel droplets which are originated by fuels with high KV and (σ), and high (ρ) causes poor and uncompleted combustion which produces unburnt hydrocarbon, carbon monoxide, and black smoke, and provokes the formation of deposits/carbon deposits in/on the parts of combustion chamber [38]. Moreover, once unburnt fuel come into the crankcase, it dilutes and degrades the lubricating oil of engines. Fuels with high KV always tend to form the fuel spray including larger droplets, which boost other negative reactions such as polymerization process, and charring formation or coking formation. On the contrary, viscous fuels show a higher effectiveness regarding lubrication ability [39]. However, it is reported that KV of fuels affects less the indirect-injection (II) engines than direct-injection (DI) engines [40][41].

It is known that engine performance and emissions are strongly affected by the fuel-air mixture quality in the combustion chamber. Additionally, the fuel-air mixture quality depends much on the fuel-droplet size, fuel homogeneity after being injected into the cylinder. Normally, the small sizes of fuel-droplets result in the large total area of heated and evaporated fuel surface. The fuel-droplet size after injection, homogeneity, and uniformity of the fuel-air mixture in the engine cylinder is thought to depend on the as-used fuel types. This means that the homogeneous atomization and spray is the main factor of producing a homogeneous fuel-air mixture. As reported, the homogeneity and uniformity of sprayed and injected fuels are determined through the diameter or size of the fuel droplets and particles, as well as their dispersion that is evaluated based on the mean diameter of the sprayed and injected particles. Thus, fuel dispersion in the cylinder depends much on fuel particle size/diameter. There are several indicators characterizing the quality of the fuel injection, however, the indicators related to fuel spray including penetration length (L_b), the ratio (SMD/d) of Sauter mean diameter (SMD) per the droplet diameter (d), and cone angle (θ) are considered as the most important. Based on Eq. (8) to Eq. (10), the injected-fuel quality into the cylinder depends on not only FSS parameters (such as injection pressure, the nozzle diameter, the high-pressure pump quality), but also physical properties of vegetable oils. According to EN 14214:2008, the effects of fuel KV on (L_b), (SMD/d), and (θ) are considered the most. However, the cone angle of fuel spray seems to be not affected by engine operating conditions. In this study, the effect of heating temperatures on the above-mentioned indicators of fuel spray is introduced, and the correlations of (L_b), (SMD/d) with heating temperatures are shown from Fig. 8 to and Fig. 9 under different test-engine speed.

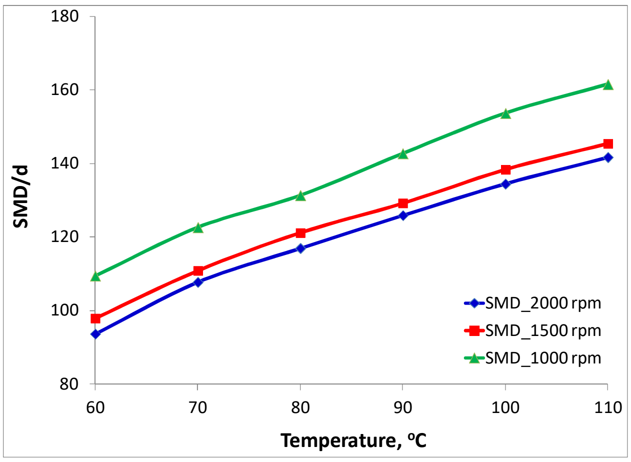

Fig. 8. SMD/d as a function of heating temperatures at different engine speed

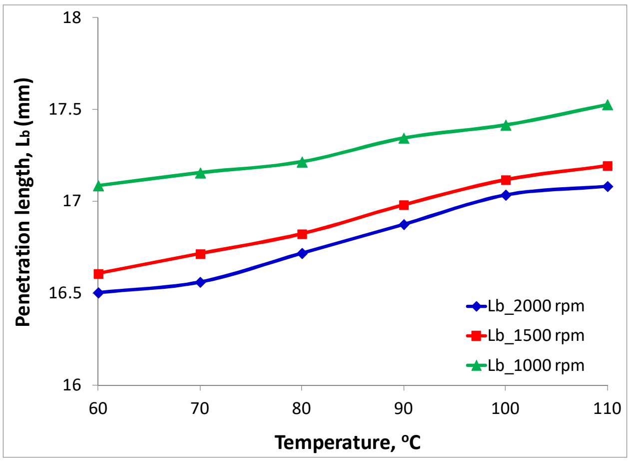

Fig. 9. Penetration length as a function of heating temperatures at different engine speed

Based on Eq. (8) suggested by Bracco for L_b, Eq. (9) suggested by Hiroyasu and Arai for SMD/d, an increase of L_b and SMD/d along with the increase in engine speed can be clearly seen. At low heating temperatures resulting in high KV and density, thus, injected fuel mass tends to increase with the same volume. In addition, at low speeds, fuel injection velocity and pressure are low leading to larger SMD and higher L_b at the same KV, σ, ρ values [28]. It is understood that low KV, σ, ρ increase injection velocity (u), and reduce the break-up time (τ_{br}) and interactive aerodynamic time (τ_e). The decrease of τ_{br} and τ_e results in increasing the dissipation, vaporization, and mixing. Further, the increase of injection velocity plays the most important part in changing the value of Re and We affecting the breakup mechanism. Therefore, the effects of fuel properties on both primary breakup and secondary breakup are ascertained. Primary breakup provides the fuel spray parameters; meanwhile, secondary breakup affects mixture formation directly. Due to the time of injection, breakup, evaporation, and mixture formation are very short (around 15-60μs for diesel engines), the fuel spray with small SMD/d and short L_b may be more suitable for the combustion to produce a higher power and lower pollution emissions. Several published works have indicated the influences of as-used vegetable oils on engine performance and emissions [42], those results may be used to illustrate and prove the achieved results from this work.

IV. Conclusions

In this study, the analysis model for vegetable oils based on either theoretical equation or experiment aiming to estimate the kinematic viscosity, surface tension and density in the relationship with heating temperatures are developed. In addition, the evaluation of influences of the as-used vegetable oil physical properties on the fuel supply system and spray characteristics are conducted. Three available types of vegetable oils were used in this study were Coconut oil, Jatropha oil, and Soybean oil. Some following conclusions are indicated:

1. Physical properties of pure vegetable oils including kinematic viscosity, surface tension, and density are inversely proportional to heating temperature. Empirical equations for prediction of the dependence of the above-

mentioned physical properties on heating temperatures are established with a high confidence level. The values R^2 = 0.9938, R^2 = 0.9954, and R^2 = 0.9961 are found to estimate relationship between kinematic viscosity, surface tension, density of as-used vegetable oils and heating temperatures, respectively. In addition, the equation regarding the dependence of kinematic viscosity and surface tension on density is also carried out on the basis of data obtained from the experiment with value R^2 = 0.9924 and R^2 = 0.9915.

2. The experimentally-evaluated impacts of vegetable oil physical properties on as-fabricated fuel supply system are conducted based on two key factors, being fuel flow rate and frictional head loss. Results show that high frictional head loss and low fuel flow rate occur at low heating temperature, according to high kinematic viscosity, surface tension, and high density of vegetable oils.

3. The parameters characterizing for spray and atomization of fuels used for diesel engines such as SMD and penetration length are determined by mathematical equations under different engine speeds. The break-up mechanism related to atomization, evaporation, mixture formation and combustion is explained from the consideration of the dependence of spray parameters on vegetable oil physical properties and heating temperatures.

NOMENCLATURE

KV	kinematic viscosity	mm^2/s
SMD	Sauter mean diameter	µm
L_b	penetration length	mm
d	fuel-droplet sizes	mm
L	fuel pipe length	mm
d_p	fuel pile diameter	mm
u	fuel velocity	m/s

Greek letters

ρ	density	$kg.m^{-3}$
σ	surface tension	mN/m
θ	cone angle	degree

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