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Diagnosing the Process of Forming Biofuel Combustion Mixtures in Diesel Engines by a Program to Compute Spray Volume

Mai Duc Nghia[1], Ho Duc Tuan[2,*]

1 Faculty of Mechanical Engineering, Air Force Officer's College, Nhatrang City, Vietnam
2 Faculty of Transportation Engineering, Nha Trang University, Nhatrang City, Vietnam

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ABSTRACT

A diesel engine's injection and combustion mixture formation process are essential; it determines the engine's economic, technical, and environmental criteria. When the engine uses biofuel, fuel parameters such as viscosity, density, and surface tension affect the above process. Each engine using a specific fuel type will have to adjust injection parameters such as injection pressure and timing to ensure the injection process and formation of a homogeneous air-fuel mixture. Therefore, through the spray structure, it is possible to diagnose the process of combustion mixture formation, thereby making adjustments to the fuel injection system that will improve engine performance and reduce emissions of toxic exhaust gases. In this study, the article presents the content of building a program to compute spray volume using Matlab software. Through the spray volume, quickly diagnose the process of forming the biofuel-air mixture in the diesel engine combustion chamber, thereby determining the appropriate fuel injection system adjustment. Results of simulation and experimental research on 4CHE Yanmar engines installed on fishing vessels with fuel types DO, B5, B10, and B15 show that the B15 fuel mixture when used for the engine needs to be increased injection pressure is about 10% higher than DO fuel injection pressure.

1. Introduction

Until now, the primary biofuels used for diesel engines have been Biodiesel or Straight vegetable oil (SVO) mixed with diesel oil (DO). However, the potential of coconut oil as a biofuel is gaining traction. With their environmentally friendly and renewable properties, biofuels are being increasingly advocated for use [1-5]. Among the various vegetable oils used as fuel for engines, coconut oil stands out for its high yield, particularly in Southeast Asian countries [6,7]. This promising potential of coconut oil as a biofuel is a beacon of hope for the future of engine technology.

Straight coconut oil does not need to be synthesized into Biodiesel but is mixed directly into diesel used as fuel through a mixture generator. However, coconut oil has high viscosity compared to diesel oil, so when mixing coconut oil with diesel oil, it is necessary to heat it to about 80^0C to reduce the

* *Corresponding author.*
E-mail address: tuanhd@ntu.edu.vn

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mixture viscosity close to the diesel fuel viscosity (DO), through which when used as fuel for the engine, the process of forming the combustion mixture will be uniform [8-11].

The fuel injection process plays a pivotal role in the formation of the combustion mixture. It ensures that the spray is evenly distributed in the combustion chamber space, facilitating thorough mixing with the air. This, in turn, accelerates the speed of evaporation and combustion. For direct injection engines, the injection process is the most effective measure to control the combustion process. The spray's kinetic energy is the primary source of vortex creation, which regulates the air-fuel mixing and the pre-mixed flame spread rate. This significantly impacts the ignition, heat release, and formation emissions, thereby influencing engine noise, fuel consumption, and emissions [12-15]. This underscores the importance of the fuel injection process in engine technology.

Figure 1 shows the states of the fuel spray. After leaving the nozzle, the fuel is divided into many different regions. The fuel particles change in each region and are concentrated in a fuel spray [16,17].

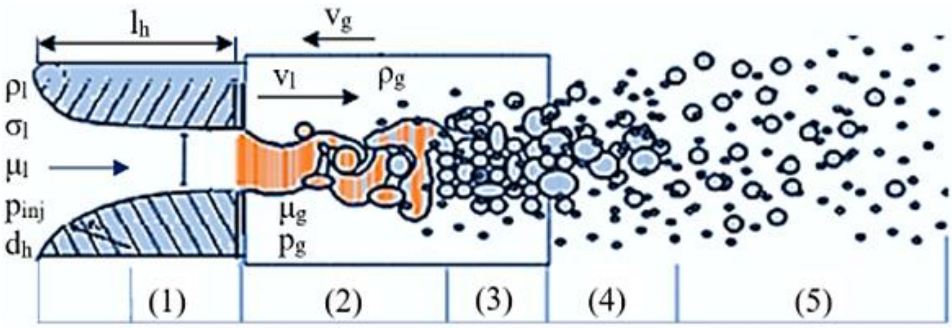

Fig. 1. States of liquid fuel spray formation

(1): The spray core area has not yet broken up (intact).
(2): The liquid phase region begins to brack up (primary break up) λ <1 (Churning). λ is the air-fuel ratio.
(3): The region is showing liquid >> gas phase (λ < 1). Due to the small distance between drops (Thick):
- There is significant interaction between fuel drop (collision, combination).
- The boundary layer of one drop affects the neighboring dops.

(4): Region representing liquid ≈ gas phase (λ = 1). The liquid phase also accounts for a significant portion of the total mass, and there is a kinetic energy transfer from the fuel drop into the gas phase that affects other drops (Thin).
(5): Liquid << gas phase region (λ > 1). The liquid phase is insignificant compared to the gas phase (Very thin).

Physical parameters that affect spray distribution include [17-21]

Liquid phase Reynolds number

$$Re_l = v_l d_h \rho_l / \mu_l \quad (1)$$

Liquid phase Weber number

$$We_l = v_l^2 d_h \rho_l / \sigma_l \quad (2)$$

Liquid phase Ohnesorge number

$$Oh = (We_l)^{1/2} / Re_l \quad (3)$$

Taylor parameters

$$T_a = Re_l / We_l = \sigma_l / \mu_l . v_l \quad (4)$$

The velocity of the injected liquid fluid (m/s)

$$v_l = C_d (2(p_{inj} - p_c) / \rho_l)^{1/2} \quad (5)$$

For the gas phase in the combustion chamber. The parameters v_l, σ_l, and ρ_l in the above formulas are replaced by the quantities v_g, σ_g and ρ_g.

Where, C_d: flow factor of the injector holes (–), $C_d \approx 0.7$ according to Lejda and Woś [22]; d_h: diameter of sprayer holes (m); μ_l: fuel absolute viscosity (kg/(m·s)); ρ_l: fuel density (kg/m^3); σ_l: fuel surface tension (N/m); p_{inj}: fuel injection pressure (Pa); p_c: pressure in the combustion chamber at the end of compression (Pa); l_h: length of injection hole.

The above physical parameters create a continuous transition of fuel in the spray from one region to another and are difficult to define clearly. On that basis, the spray jet description is characterized by the spray volume, including the parameters break-up length, spray tip penetration, and spray cone angle, as shown in Figure 2 [23].

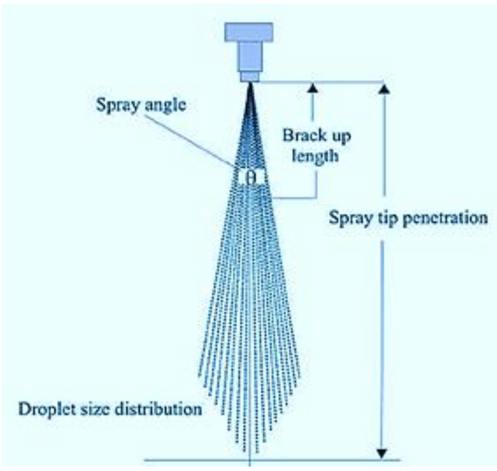

Fig. 2. Physical parameters of a fuel spray

Break-up length (l_b): The liquid fuel does not break up immediately after leaving the nozzle hole but undergoes a certain part of the spray to disintegrate into the drop. That length is called the break-up length l_b (m). The lb length is important in determining mixing ability when injecting fuel into the combustion chamber [23,24].

Break-up length l_b is calculated according to the following formula [25]

$$l_b = 2,65^{-3} d_h We_l^{-0,1} Re_l^{-0,3} \left(\rho_l / \rho_g\right)^{-0,08} \quad (6)$$

Spray tip penetration (S): The spray tip penetration S (m) is limited by the distance between the nozzle and the piston top [20]. The time to develop the penetration S of the spray starts at the tip of the nozzle (needle lift begins to open) and ends when the liquid from the nozzle holes begins to break up. Due to the small needle lift stroke and low flow volume at the beginning of injection, the growth of S is linear with time. Several experiential formulas have been proposed, in which the spray tip penetration is expressed through formula 7 [26,27].

Spray tip penetration at specified crankshaft angle position:

$$S(\varphi) = ((d_h.v_l\left|\varphi - \varphi_{inj}\right|) / (6n.\sqrt{2}.a_u))^{1/2} \tag{7}$$

$$a_u = C_1.W_e^{\ k}.Lp^l.M^m \tag{8}$$

$$Lp = \rho_l.\sigma_l.d_h / \mu_l^2 \tag{9}$$

$$M = \rho_g / \rho_l \tag{10}$$

where,

W_{el}, V_l calculated according to the formula 2, 5;
Lp: dimensionless Laplace criteria number (–);
M: air to fuel density ratio (–);
n: the engine speed (rpm);
φ : crankshaft angle position (deg);
φ_{inj} : injection timing (deg);
a_u: factor of free-stream turbulence in the spray tip layer (-), a_u depends on Table 1 [27].

Table 1
The experimental constants C_1, k, l, and m values were used to calculate spray tip penetration

For high back pressure (M = 0.0095 - 0.028)	For low back pressure (M = 0.0014 - 0.0095)
C_1 = 2.72	C_1 = 0.202
K = − 0.21	K = − 0.21
L = 0.16	L = 0.16
m = 1	m = 0.45

If l_b is too great, it will directly affect the spray tip penetration and the ability of the spray to break up. If l_b is too short, it will reduce the ability of the beam to disperse in the combustion chamber space. The above factors depend on the jet velocity (or injection pressure, p_{inj}) and the gas pressure in the combustion chamber (pressure in the combustion chamber at the end of compression), directly affecting the process of spray cone angle (θs): The spray cone angle θs is the angle formed by two spray geometric boundaries from the nozzle mouth. The cone angle usually has a magnitude of 5 ÷ 30deg. Increasing the cone angle only reaches a certain value. Increasing too large will reduce the spray penetration and may cause vaporization right at the nozzle mouth. On the other hand, if the cone angle is reduced too low, it will increase the spray tip penetration, leading to a collision with the piston wall and top [28]. In previous studies, there have been proposals to determine the spray cone angle, especially according to Naber and Siebers [29].

Spray cone angle

$$\tan(\theta_s / 2) = 0,3173\left(\rho_g / \rho_l\right)^{0,1017} \quad (11)$$

2. Research Objects and Methods

2.1 Research Objects

Table 2 gives basic fuel specifications: DO (100% diesel oil), B5 (5% vegetable oil, 95% diesel oil), B10 (10% vegetable oil, 90% diesel oil), and B15 (15% vegetable oil, 85% diesel).

Table 2
Basic fuel specifications of the diesel-coconut oil mixture

Fuel	Density (g/cm^3)		Cetane number (CN)	Kinematic viscosity (medium mm^2/s)		Calorific value (Kcal/kg)	Ignition temperature (^{0}C)
DO (100% diesel oil)	0.8360	at 40^{0}C	50	3.250	at 40^{0}C	10478	Min 60
B5 (5% vegetable oil)	0.8369	at 80^{0}C	54	3.254	at 80^{0}C	10775	70
B10 (10% vegetable oil)	0.8372		53	3.267		10675	73
B15 (15% vegetable oil)	0.8420		52	3.652		10650	75

2.2 Research Methods

Using Matlab software to build a program to simulate fuel spray volume and conduct experimental research to verify it on a 4CHE Yanmar diesel engine installed on a fishing vessel. Engine and research parameters are given in Table 3.

Table 3
Engine and research parameters

Chamber type	Unified
Number of cylinders	4
Cylinder diameter x piston stroke (mm)	105x125
Power (Hp/rpm)	70/2300
Compression ratio	16.4
Number of nozzle holes x diameter x spray direction	4 x 0.32 x 140^0
Injection timing ^{0}BTDC	18^0
Injection pressure (bar, Pa)	210÷240, (210÷240).10^5
Engine speed of simulation and experiment (rpm)	1400
Load (%)	60

Considering the variation of the fuel mixture spray when injected into the combustion chamber (Figure 3), assume the density distribution of fuel drops in the spray is the same in all directions. Varying the volume of the fuel spray (V_t) is determined according to Eq. (12) [29].

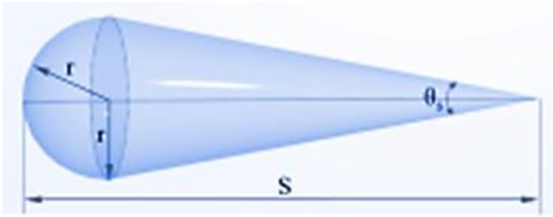

Fig. 3. Model of fuel spray variation in the engine combustion chamber

$$V_t(\varphi) = i/3\left[\pi.\left(S(\varphi)/(ctg\theta_s+1)\right)^2.S(\varphi).\left(1-1/(ctg\theta_s+1)\right)+2\pi.\left(S(\varphi)/(ctg\theta_s+1)\right)^3\right]$$
$$V_t(\varphi) = \left[(i.\pi.S(\varphi)^3)/3\right].\left[1/(ctg\theta_s+1)^2+1/(ctg\theta_s+1)^3\right] \quad (12)$$

Eq. (12) represents the instantaneous volume of the fuel spray. On that basis, when considering the injection process, the change in volume V_t varies with the degree of crankshaft rotation

$$\frac{dV_t}{d\varphi} = i.\pi.S(\varphi)^2.\left[1/(ctg\theta_s+1)^2+1/(ctg\theta_s+1)^3\right].dS/d\varphi$$
$$\frac{dV_t}{d\varphi} = i.\pi.S(\varphi)^2.\left[1/(ctg\theta_s+1)^2+1/(ctg\theta_s+1)^3\right].v_S(\varphi) \quad (13)$$

$$v_s(\varphi) = dS/d\varphi = d_h.v_l/2\sqrt{2}.a_u.S(\varphi) \quad (14)$$

where,

i: number of holes in the sprayer (-); $V_t(\varphi)$: instantaneous total volume of the spray (m^3); $dV_t/d\varphi$: change of total volume (m^3/deg); $v_s(\varphi)$: spray tip velocity at specified crankshaft angle position (m/deg); $S(\varphi)$ calculated according to Eq. (7). Then, the mathematical relationship between injection pressure, injection timing, and fuel spray volume is expressed through Eq. (15)

$$dV_t/d\varphi = \left[i.\pi.(((d_h.C_d.(2(p_{inj}-p_c)/\rho_l)/(6n.\sqrt{2}.a_u)).\left|\varphi-\varphi_{inj}\right|)^{1/2}\right]$$
$$.\left[1/\left(ctg0,05\left(d_h^2.\rho_g.(p_{inj}-p_c)/\mu_g^2\right)^{0.25}+1\right)^2+1/\left(ctg0,05\left(d_h^2.\rho_g.(p_{inj}-p_c)/\mu_g^2\right)^{0.25}+1\right)^3\right]$$
$$.\left[d_h.C_d.(2(p_{inj}-p_c)/\rho_l)^{1/2}/2\sqrt{2}.a_u\right] \quad (15)$$

The injection start timing is φ_{SOI}; the combustion start timing is φ_{SOC}. During the period from $\varphi_{SOI} \div \varphi_{SOC}$, V_t is determined according to Eq. (16).

Eq. (16) shows that injection pressure and fuel injection timing almost determine the injection spray volume. The fuel's specific density also has a significant influence. As the fuel density increases, the fuel spray length increases, and the fuel drop size also increases. After leaving the nozzle, the spray begins to break into a spray cone; this is the first breakup of the liquid, called primary breakup. This process develops over the time of injection, creating the fuel spray structure [29].

$$V_t = \left[i\pi \int_{\varphi_{SOI}}^{\varphi_{SOC}} (((d_h.C_d.(2(p_{inj} - p_c)/\rho_l))/(6n.\sqrt{2}.a_u)).\left|\varphi - \varphi_{inj}\right|)^{1/2} \right]$$
$$.\int_{\varphi_{SOI}}^{\varphi_{SOC}} \left[1/(ctg0,05\left(d_h^2.\rho_g.(p_{inj} - p_c)/\mu_g^2\right)^{0.25} + 1)^2 + 1/(ctg0,05\left(d_h^2.\rho_g.(p_{inj} - p_c)/\mu_g^2\right)^{0.25} + 1)^3 \right] \quad (16)$$
$$.\left[\int_{\varphi_{SOI}}^{\varphi_{SOC}} (d_h.C_d.(2(p_{inj} - p_c)/\rho_l)^{1/2}/2\sqrt{2}.a_u).d_\varphi \right]$$

Matlab Simulink software allows the analysis, modeling, and simulation of linear, nonlinear, continuous, and discrete processes visually in a graphical communication environment with simple operations. A model will be built in Simulink to simulate the fuel spray structure based on a set of representative blocks. In it, blocks are used to create, edit, combine output, and display data; paths transfer data from one block to another. The main blocks used in the model are as [30]

Sources: used to create the data; Sinks: used to represent data.
Continuous: represents system elements continuously over time.
Operation math: contains mathematical expressions.

On that basis, the fuel injection process will be built using Matlab software with appropriately modified equations.

3. Research Results and Discussion

3.1 Simulation Research

Modeling the spray calculation process in Matlab Simulink software is shown in Figure 4.

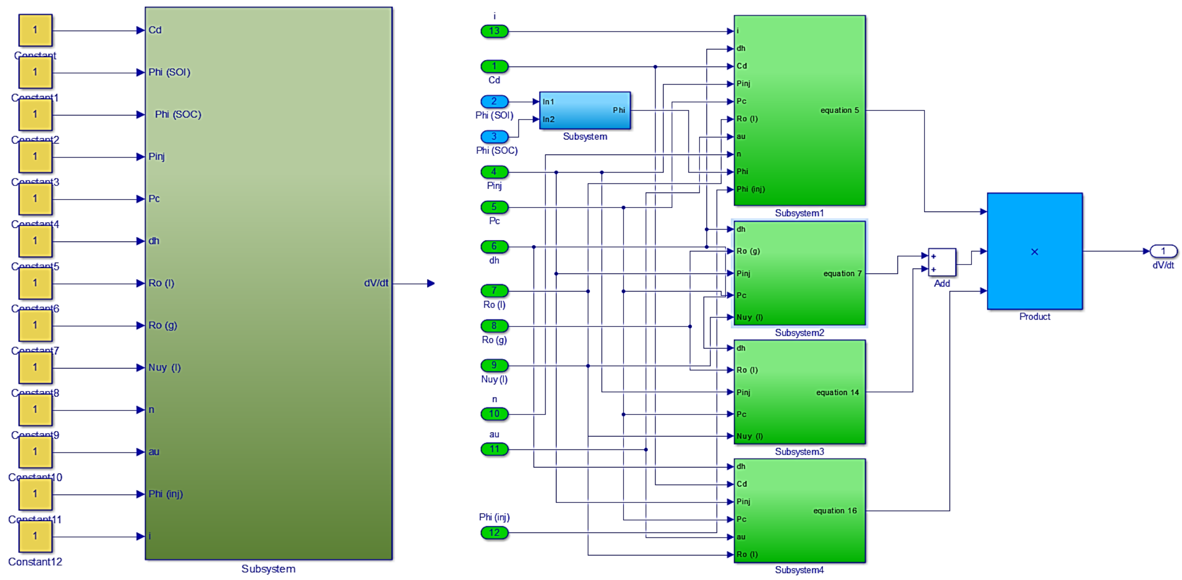

Fig. 4. Spray simulation model in Matlab software

Figure 5 shows the calculation program interface. The DO fuel is calculated to compare with biofuels with different mixing ratios.

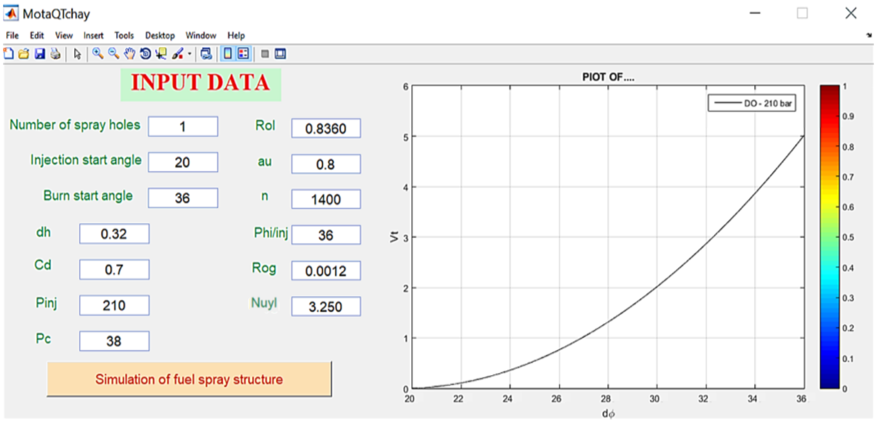

Fig. 5. Fuel spray calculation program interface

Figure 6 presents the calculation results of different fuel types compared to DO fuel. Under the same injection conditions, the difference in the fuel's physicochemical properties is a factor that leads to differences in fuel drop diameter, affecting the level of fuel vaporization. This process leads to a change in spray volume. The difference in density, kinematic viscosity, and surface tension of the diesel-coconut oil mixture changes the structure of the mixed fuel spray compared to diesel oil.

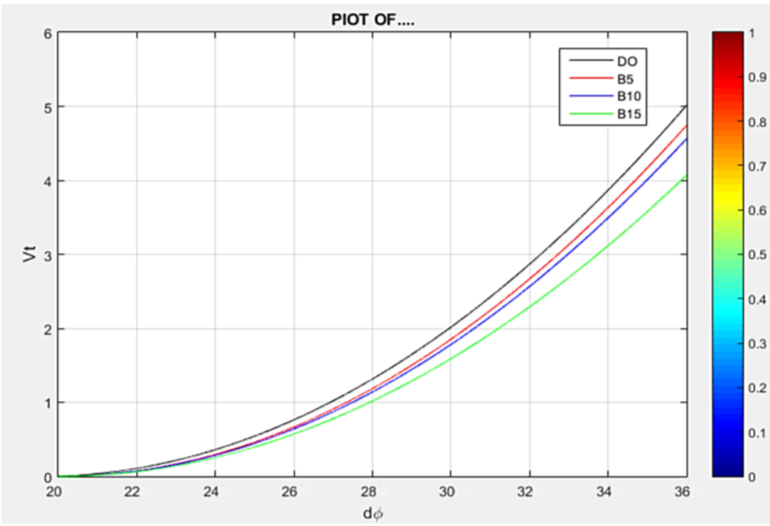

Fig. 6. Spray volume of biofuel mixed at different ratios compared to DO fuel

Figure 6 shows that B15 fuel has the smallest volume. Due to its high viscosity and surface tension, it leads to a decrease in spray velocity and the decrease in spray volume. On this basis, the spray volume should be increased by increasing the B15 fuel injection pressure from 210 bar to 230 bar and 240 bar. At 240 bar, the B15 fuel spray volume tends to be larger than that of DO fuel in the early stages of the injection process but decreases in the later stages. It shows that a nonlinear value appears when increasing the injection pressure, meaning that it can only grow within a specific range, as shown in Figure 7.

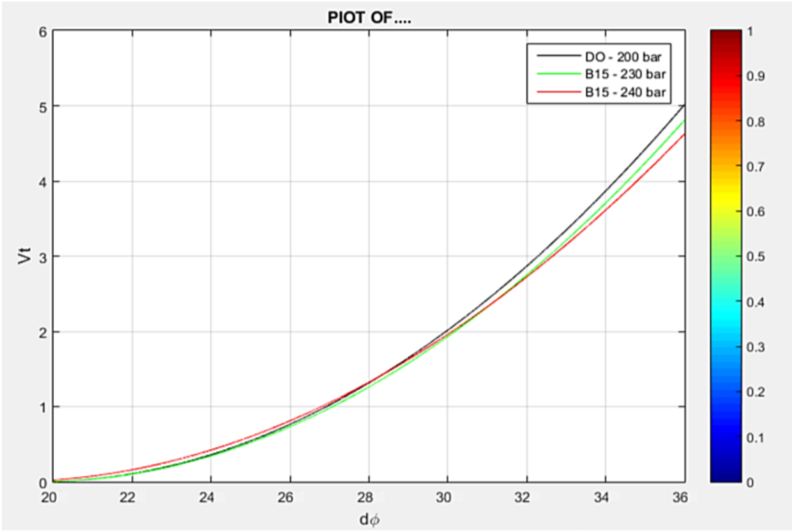

Fig. 7. Comparison of B15 fuel spray volume when increasing injection pressure with DO fuel

Figure 8 compares the spray volume value of B15 fuel before and after increasing injection pressure to DO fuel. Based on the simulation results, it can be seen that under the same injection conditions with DO fuel (injection pressure), the B5 fuel spray volume is equivalent to DO fuel, followed by the B10 fuel mixture. Only minor fuel system adjustments can be made when using B10 when using the above fuels for the engine. Particularly for the B15 mixture, the spray volume is too small compared to the remaining samples, so the process of forming the combustion mixture will decrease, leading to reduced power and increased emissions. Therefore, when used in engines, it is necessary to increase injection pressure to ensure the formation of a highly effective combustion mixture. It will increase power and reduce emissions for diesel engines, mainly soot.

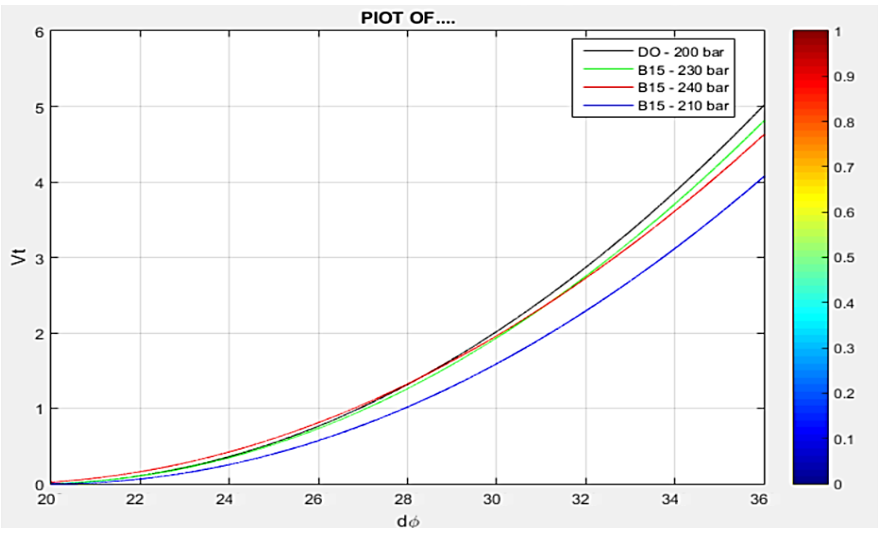

Fig. 8. Comparison of B15 fuel spray volume with DO fuel in different injection pressure cases

3.2 Experimental Research

Experimental research compares the engine's power and soot emissions when using fuel sample B15 to DO in cases where the injection pressure changes. The spray volume calculation program is built into Matlab software as a basis for evaluating the spray volume calculation program.

Figure 9 shows the experimental layout diagram, and Figure 10 shows the image of the engine and experimental equipment. The tank mixes diesel fuel with coconut oil heated from the engine's coolant, which is about 80^0C.

The experimental equipment includes equipment MSA-PC-SE.NR 00601 of Germany is used to measure smoke opacity (Soot – N%); Dynomite 13 hydraulic brake of LAND SEA- USA, with computer connection, is used to cause load and calculate power. The load on the motor is done through torque adjustment in hydraulic brake M_b (N.m)

$$M_b = G_w.C.(T_{in} - T_{out}) \quad (17)$$

The engine torque M_e (N.m) will be equal to the sum of the torque calculated on the dynamometer and the torque in the hydraulic brake

$$M_e = M_b + p.l \quad (18)$$

Engine power N_e (kW/h) is determined

$$N_e = n.M_e/9550 \quad (19)$$

In the above formulas: G_w: the amount of water required for the brake to work (kg); C: the specific heat of water (J/kg.K); T_{in}, T_{out}: the temperature at inlet and exit brake (K); p: dynamometer (N); l: swing arm length (m); n, test engine speed (rpm).

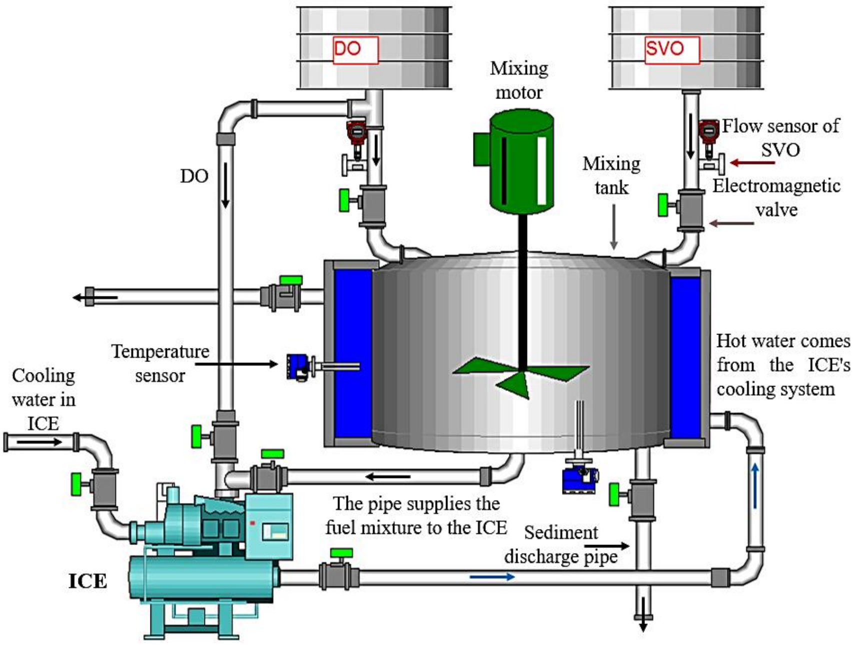

Fig. 9. Fuel supply diagram for the engine

Fig. 10. Engine and experimental equipment

When the engine works stably with DO fuel at idle mode and reaches a coolant temperature of about 80 °C, apply a load (60%), increase speed (1400 rpm), and change fuel to measure power values and soot emissions.

In the cases of not increasing and increasing injection pressure, the results of measuring the power of the fuel types are shown in Figure 11.

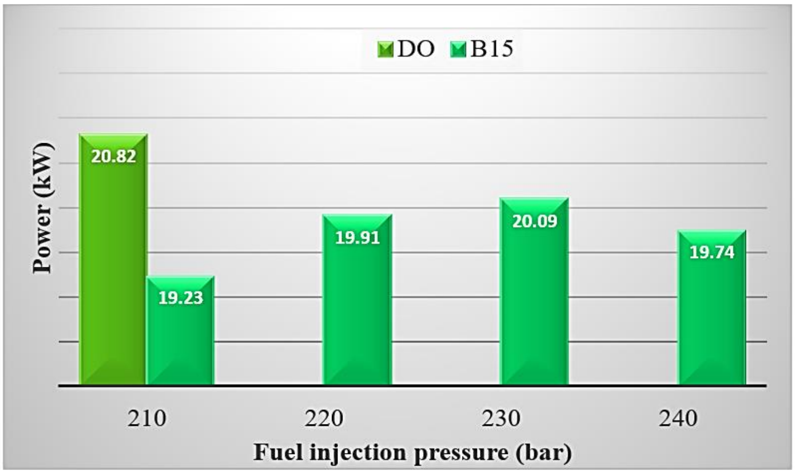

Fig. 11. Comparison of engine power when using B15 and DO fuel

When increasing the B15 fuel injection pressure to 230 bar, the above results show that increasing injection pressure causes the spray structure to increase, creating a more homogeneous air-fuel mixture formation process, leading to increased combustion efficiency and increased combustion temperature, causing power to increase, and soot to decrease due to increased soot oxidation process.

However, at an injection pressure of 240 bar, the B15 fuel spray tends to vaporize early in the early stages of the injection process. It is appropriate with the simulation results when, in the early stages of the injection process, the spray volume of B15 fuel is more extensive than other fuel samples, leading to the formation of a heterogeneous mixture, causing incomplete combustion, leading to reduced power and increased soot emissions as on Figure 12.

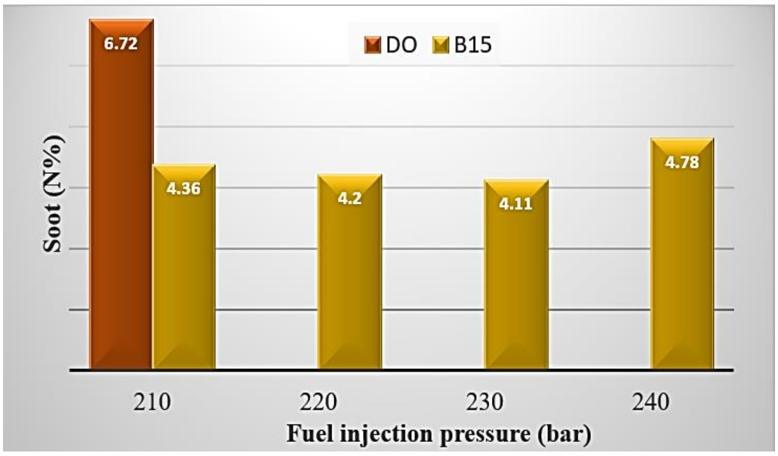

Fig. 12. Comparison of engine soot emissions when using B15 and DO fuel

4. Conclusions

The research results have built a program to quickly calculate the spray volume in the combustion chamber of a diesel engine using Matlab software. The results of the calculation and analysis of the fuel spray volume of the coconut oil-diesel mixture from the simulation program are consistent with experimental results on a 4CHE Yanmar diesel engine installed on a fishing vessel. Experimental results show that, with B15 fuel, it is necessary to increase the injection pressure by about 10% compared to traditional fuel (DO). It will make forming the combustion mixture more effective, increasing the power and reducing emissions but not growing injection pressure too great.

Through the spray simulation program, the process of combustion mixture formation can be diagnosed, thereby providing a level of fuel injection system adjustment suitable for each type of biofuel used for diesel engines.

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