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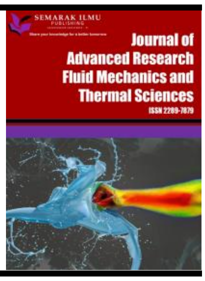

Study to Establish the Relationship Between Fuel Injection Parameters and Exhaust Emission Content of Fishing Vessels' Diesel Engines to Diagnose the Technical State

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ABSTRACT

Fuel injection parameters of diesel engines are essential. It directly affects the process of forming the combustion mixture, fuel combustion, and emission formation. The fuel injection pressure with the pressure at the end of the compression stroke in the engine cylinder at the time of fuel injection is worth noting. If the above parameters are reduced compared to the technical requirements, the combustion process is incomplete, and soot emissions increase. On that basis, the article studies the relationship between fuel injection parameters and exhaust emissions by simulation and experimental methods, through which it is possible to recognize emission results for the diagnosis technical state of the fuel injection system and the group that encloses the engine's combustion chamber. Research results on the 6CHE Yanmar diesel engines of the fishing vessels at zero load conditions show that. When soot emissions increase by more than 20%, the fuel injection pressure is reduced compared with technical requirements. The fuel injection system and the group that encloses the combustion chamber need to be maintained on time to prevent damage incidents that may occur and to ensure the safety of people and fishing vessels when operating at sea for a long time.

1. Introduction

Vietnam's fishing is a traditional profession, so the use of the main engine of fishing vessels is mainly according to the custom (habits) of fishermen. Maintenance and repair work is not up to standard. The technical supervision of the main machine by the registry office is not specific because of the lack of testing equipment [1,2]. Therefore, the diagnostic work of the technical state of the main machine needs attention.

Therefore, determining the relationship between exhaust emissions, mainly soot emissions and fuel injection pressure at the injectors (p_{inj}), to diagnose the technical state of the engine (fuel injection system) before taking off the ship to make a long journey on the sea is one of the critical

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requirements, contributing to the safe operation of the engine and timely preventing and correcting any damage that occurs.

Diesel engines general, and diesel engines used in fishing vessels private are engines that burn fuel by compression or self-ignition. The operating principle and structure of all types of marine and road diesel engines are the same, differing mainly in the operation mode and working environment [3-5].

Diesel engines used in fishing vessels are medium or high-speed engines with a rotational speed of 1500 - 3000 rpm, but because of their frequent characteristics of working in wet environments, operating conditions are harsher than diesel engines on the road, so diesel engines used for fishing vessels need to have great power, and be able to operate stably in the exploitation modes for a long time, continuously, in the environment with often changes in physical conditions (temperature, humidity, Etc.) and chemical (ratio of salt in the air) [6-8].

Diesel engines used as main engines on fishing vessels are abundant, diverse, and bulk focus on the longtime famous manufacturing company chosen by fishermen. Survey data on types of diesel engines as main engines installed on the fishing vessels in the south-central coastal area of Vietnam are shown in Figure 1, and specifications of the main engines for the fishing vessels are shown in Table 1 [1,2,7,9,10].

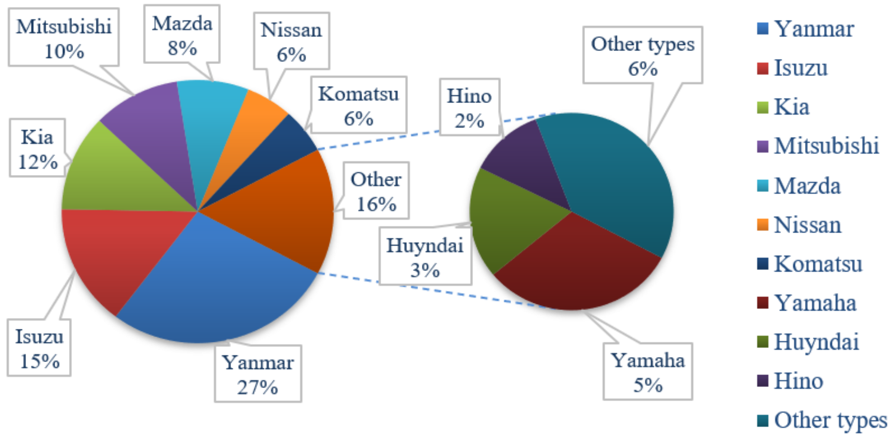


Fig. 1. Types of engines for the main machine of the fishing vessels

Table 1
Specifications of common diesel engines used as the main machine of the fishing vessels

Parameters	Symbol	Unit	Value
Speed	n	rpm	1500 - 2300
Compression ratio	ε	-	14-17
Type of combustion chamber	ω	-	Unified
Fuel injection system	-	-	Direct, multi-hole nozzle
Fuel injection pressure	pinj	bar	200 - 220
Exhaust gas temperature (maximum)	Tx	0C	450 - 550

The fuel injection pressure parameter affects the spray structure, especially for engines with a unified combustion chamber, thereby directly affecting the formation of the combustion mixture and fuel combustion, leading to changes in performance indicators of diesel engines, including exhaust emissions (soot) [11-15].

In fact, in Vietnam today, the diesel engines used as the main engines on fishing vessels are mostly old engines that have been used for many years. That leads to reduced safety, reduced reliability during exploitation, low efficiency of use, and especially sudden damage at sea, endangering people and ships.

When the engine is running, the measurement of exhaust emissions (soot) is simple, feasible, and reliable through a small, compact measuring device. Based on the measured results, it is possible to determine the technical state of the fuel injection system, fuel properties, condition of the details of the group enclosing the combustion chamber (wear, clearance), operating mode (load, speed), thereby taking specific remedial measures, reducing time and costs.

In the exhaust gas of diesel engines, soot is a pollutant that is very dangerous to human health, which exists in the form of solid particles, is insoluble in water, and is very easy to penetrate deep into the lungs [7,10,16].

Many studies build mathematical models to predict characteristic parameters of the soot. Simple one-dimensional soot generation models have been established to calculate the flame burning outside the atmosphere and inside the engine combustion chamber.

More complex multilateral models have been developed to simulate and calculate soot emissions. Whether the models are simple or complex, they are all based on the fundamental soot generation theory, in which the model of Tesner-Magnussen is most used [7,17,18].

According to that model, the amount of soot emission received after the exhaust valve is the difference between the amount of soot formed and the amount of soot oxidized. Soot oxidation is highly dependent on the soot concentration (C_s), turbulence kinetic energy (k) and flame turbulence dissipation rate (ε), injection time, injection pressure, and pressure in the cylinder at the time of fuel injection [5,7,11]

$$r_i = A.C_s.\left(\frac{\varepsilon}{k}\right) \tag{1}$$

k and ε calculated according to Eq. (2) and Eq. (3) [17,19]

$$k = \frac{3}{2}.v_l^2 \tag{2}$$

$$\varepsilon = \frac{6\gamma.p_{inj}.n}{\rho_l.\Delta\theta} \tag{3}$$

The velocity of the fuel spray [11]

$$v_l = C_d\sqrt{\frac{2(p_{inj}-p_c)}{\rho_l}} \tag{4}$$

Injection parameters related to oxidation and soot emission are shown by Eq. (5)

$$r_i = A.C_s.\frac{1}{3}.\frac{\gamma.p_{inj}.6.n}{\Delta\theta.C_d^2.(p_{inj}-p_c)} \tag{5}$$

where *A:* constant, [-]; r_i*:* soot oxidation rate, [-]; *γ:* constant representing the turbulence energy of the mixture formation process, [-]; $\Delta\theta$*:* Fuel injection time, [deg]; ρ_l: density of fuel, [g/cm^3]; *n:* engine speed, [rpm]; C_d*:* nozzle expansion coefficient, [-]; p_{inj}*:* fuel injection pressure, [bar]; p_c*:* the end of the compression stroke pressure, [bar].

Eq. (5) shows that the soot formation and emission process in engine exhaust depends on many factors, including fuel injection pressure and the end of the compression stroke pressure. When the technical condition of the fuel injection system is not guaranteed, it will directly affect the fuel injection process into the engine cylinder, making the combustion process less efficient and increasing exhaust emissions.

The change in fuel injection pressure will affect the uniformity of the injection process (atomization), and the injection process affect the distribution of fuel drops in the combustion chamber space. If the distribution is small (spray cone angle, spray penetration), it will lead to an increased soot emission formation process [11,20-22].

From the above analysis, it is possible to describe the relationship between the factors to soot emission shown in Figure 2. If fuel and end-compression stroke pressure is not considered, then from the soot emission level is possible to evaluate fuel injection parameters, thereby identifying the possibility of damage to the fuel injection system and taking timely remedial measures.

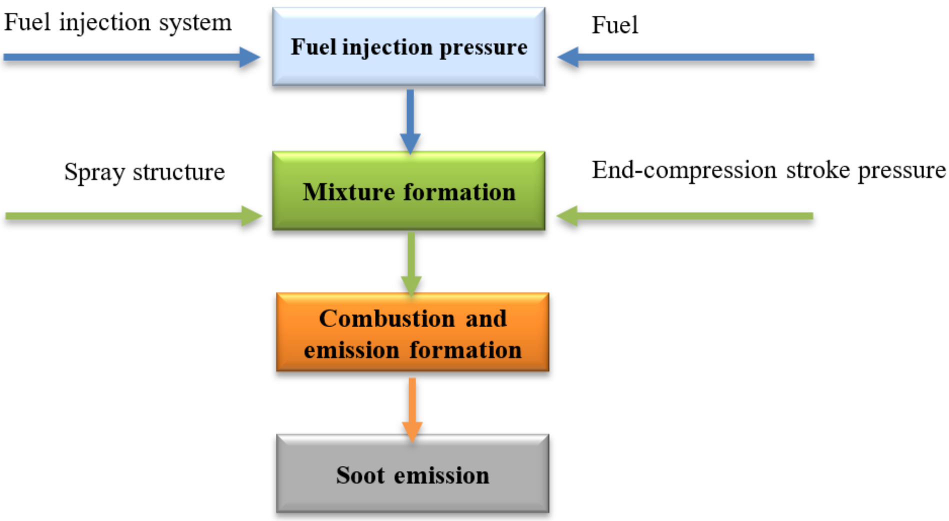


Fig. 2. Diagram describes the influence of factors on soot emission

The diagram in Figure 2 simulates the effect of injection pressure on the jet structure, thereby evaluating the formation of the combustion mixture, and then an experimental study to determine the effect of injection pressure on soot emissions, thereby assessing the technical status of the fuel injection system when other working conditions of the engine are normal.

2. Materials and Research Methods

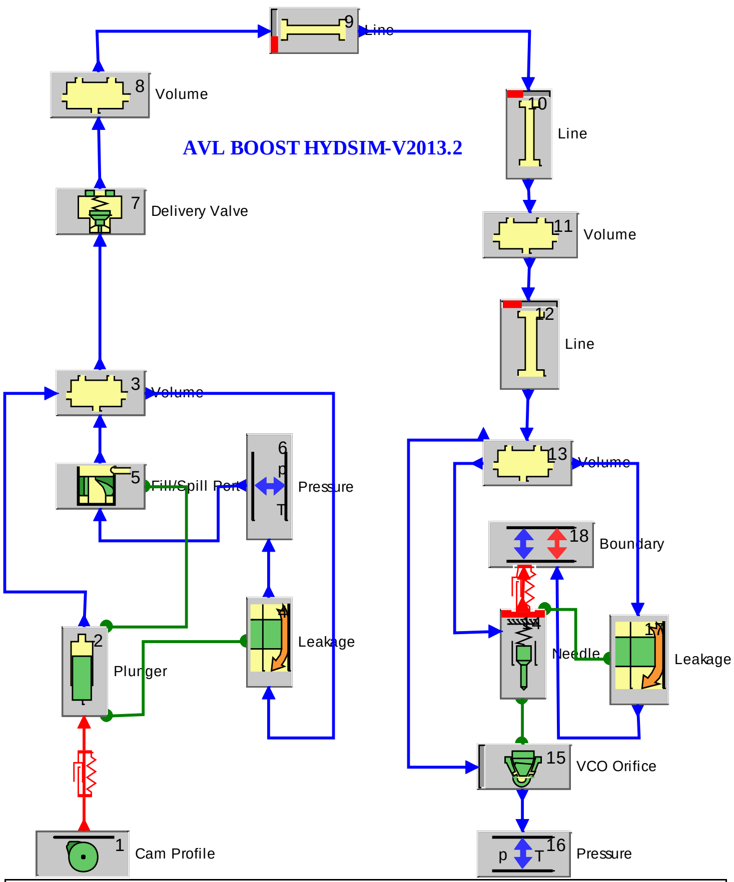
From Table 1 and Figure 1, the research engine selected is the 6CHE diesel engine produced by Yanmar Company, which is the engine commonly used as the main machine of fishing vessels. The engine parameters are shown in Table 2.

In this study, the paper uses simulation and experimental research methods: the basis of the simulation is to use AVL Boots Hydsim software of AVL Company, Austria, which is specialized software for simulating fuel injection systems [23].

The simulation model of the research engine fuel system is shown in Figure 3.

Table 2
Specifications of the Yanmar 6CHE diesel engine and experimental - simulation modes

Parameters	Value
Type of engine	6CHE
Combustion chamber	Unified
Number of cylinders	6
Cylinder diameter x piston stroke, [mm]	105x125
Power, [Hp/rpm]	105/2300
Compression ratio, [-]	16.4
The engine speed of experimental and simulation, [rpm]	1600
Number of nozzle holes x diameter x spray direction	4 x 0.32 x 140^0
Injection timing ^{0}BTDC	18^0 BTDC
Standard injection pressure, [bar]	210
The experimental and simulated injection pressure, [bar]	210; 193; 189; 185; 168; 166
Experimental fuel	Diesel oil-TCCS03:2015/PLX



1 - cam profile; 2 – plunger; 3, 8, 11, 13 – volume; 4, 17 – leakage; 5 – fill/spill port; 6, 16 – pressure and temperature; 7 – delivery valve; 9, 10, 12 – line; 14 – needle; 15 – VCO orifice; 18 – boundary

Fig. 3. The Yanmar 6CHE diesel engine fuel system model

Input parameters and calculation equation

Calculation of average fuel drops diameter according to Knight's formula [23]

$$d_{32} = \frac{1.605.\mu_l^{0.215}.\dot{m}^{0.209}.\left(\frac{A}{A_p}\right)^{0.916}}{\Delta p^{0.458}} \tag{6}$$

Calculation of spray cone angle according to Sitkei's formula (Figure 4) [23]

$$\alpha = 0.03824\frac{d_{hole}.\rho_g^{0.1}.\Delta p^{0.35}}{l_{hole}^{0.3}.\rho_l^{0.45}.\mu_l^{0.7}} \tag{7}$$

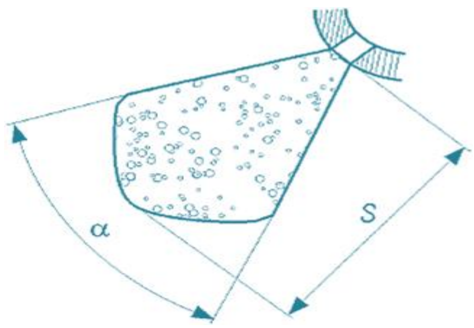


Fig. 4. Spray cone angle (α) and spray penetration (*s*)

Calculation of spray penetration according to Hyroyasu's formula (Figure 4) [11,23].

$$S = 0.39t\sqrt{\frac{2}{\rho_l}.\Delta p} \tag{8}$$

where μ_l: the kinematic viscosity of the fuel, [mm^2/s]; $\dot{m}$: mass flow rate, [mg/ms]; $\frac{A}{A_p}$: nozzle geometry with the ratio of area, $\left(\frac{A}{A_p} = 1\right)$; ρ_g: density of air, [g/cm^3]; Δp: the pressure difference, $(\Delta p = p_{inj} - p_c)$; d_{hole}: injection hole diameter, [m]; l_{hole}: injection hole length, [m]; *t*: time counted from the start of fuel injection, [s].

The simulation input parameters and the experimental mode are shown in Table 2. The experimental setup and experimental equipment are shown in Figure 5 and Figure 6.

The device Msa-pc-se. nr 00601 is the application to measure the smoke opacity of diesel engine exhaust. Which is of Beissbarth - Germany, and measurement program interface, used to measure soot emissions through the exhaust smoke opacity. The Msa-pc uses local flow measurement technology to directly and continuously measure the supplied exhaust gas samples. The measurement technique is basic on the coverage of the exhaust sample in the measurement range, from transparent to completely dark. The transparency level is recognized as no smoke in the sample tube (0%), and the dark level confirms as completely covered (99.9%). Opacity (N%): 0 - 99.9%.

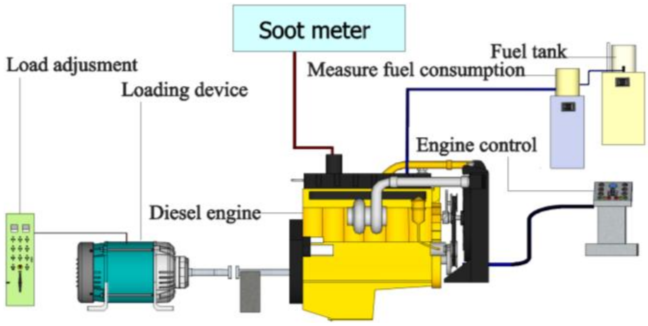


Fig. 5. The experimental setup

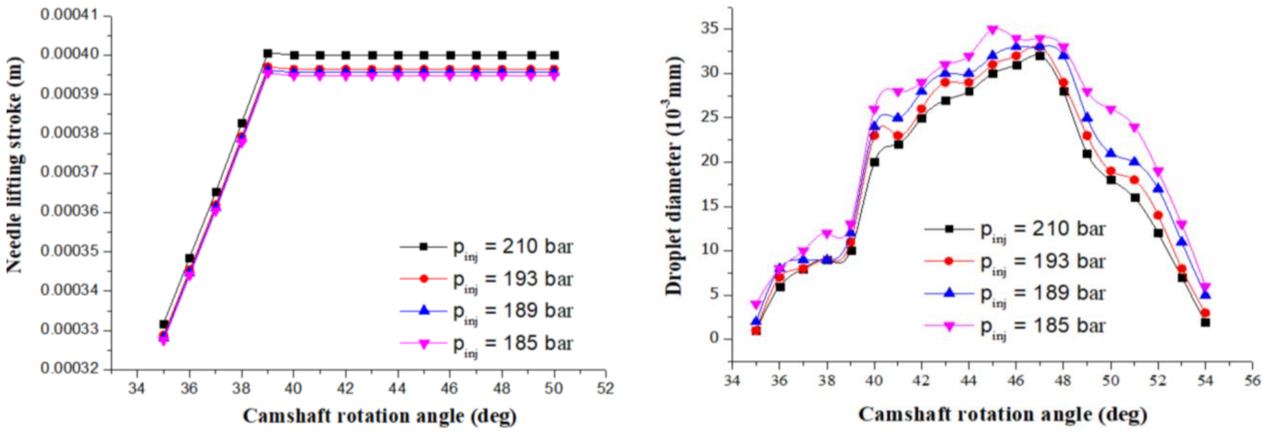
1- Engine, 2- Engine speed control, 3-The computer displays the soot measurement data, 4- NO_x measuring equipment (Testo 350 XL), 5- Soot measuring equipment (Msa-pc-se. nr 00601)

Fig. 6. Engine and measuring instruments in the laboratory

3. Research Results and Discussion

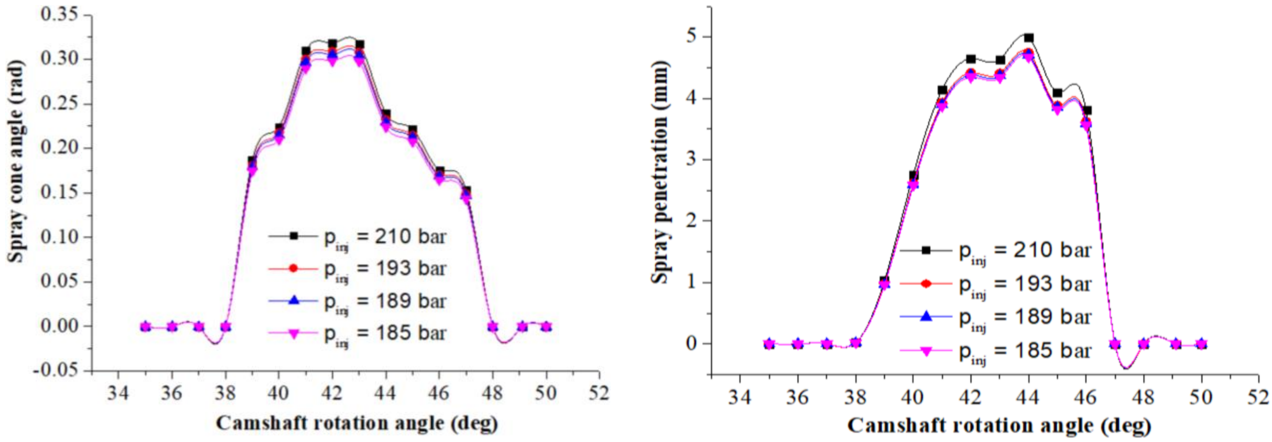
3.1 The Effect of Injection Pressure on Spray Structure

From the simulation results as shown in Figure 7 and Figure 8, when the injection pressure is reduced from 210 bar to 193 bar, 189 bar, and 185 bar (reduced respectively 8%, 10%, and 12% compared to the standard value 210 bar), low needle lifting stroke, great fuel drop diameter, short spray penetration, spray cone angle is small, this leads to the limited distribution of fuel in the combustion chamber space, which is the cause of fuel mixing - not uneven air, increasing soot formation.



(a) (b)

Fig. 7. (a) Needle lifting stroke and (b) fuel drop diameter



(a) (b)

Fig. 8. (a) Spray cone angle and (b) spray penetration

3.2 The Effect of Injection Pressure on Soot Emission

The machine operates in natural conditions with an ambient temperature of about 32 - 35^{0}C. Before processing the experiment, the engine and measuring devices are checked to ensure accuracy, which is adjusted to conform to the manufacturer's requirements.

At the beginning of the experiment, the engine started and worked at no-load mode for about 45 minutes until the engine reached a steady state in terms of coolant temperature and lubricating oil temperature

i. Cooling water temperature: about 80^{0}C.
ii. Lubricating oil temperature: about 80^{0}C.

Experimental results when adjusting injection pressure are present in Table 3. Soot emission increases when injection pressure decreases through data Table 3, the least squares method is used to build the relationship between soot emissions and injection parameters (establish the function y = f(x)).

Table 3
Soot emission measurement results

The experimental mode	Value					
Soot emission, [N%]	3.76	3.90	4.04	4.15	4.35	4.49
Fuel injection pressure, [bar]	210	193	189	185	168	166

The functional relationship y = f(x) with y representing the soot emission level, and x representing the injection pressure drop.

3.3 Experimental Data Processing

Use the least squares method to make the experiment formula and find the functional relationship between two quantities, x, and y. The function relationship y = f(x) with y representing the soot emission level and x representing the injection pressure drop.

Choose a function of the form: $y = ax^2 + bx + c$

wrong number: $vi = (ax^2 + bx + c) - y_i$ with i = 1, 2 ,..., n

Set up the spreadsheet as follows (Table 4).

Table 4
The method of calculating the sum of x and y in the experiment function

n	x_i	y_i	x^2_i	x^3_i	x^4_i	x_iy_i	$x_iy^2_i$
1	210	3.76	441.10^2	9261.10^3	194481.10^4	789.6	2968.896
2	193	3.90	37249	7189057	1387488001	752.7	2935.53
3	189	4.04	35721	6751269	1275989841	763.56	3084.782
4	185	4.15	34225	6331625	1171350625	767.75	3186.163
5	168	4.35	28224	4741632	796594176	730.8	3178.98
6	166	4.49	27556	4574296	759333136	745.34	3346.577
	$\sum x_i$ =	$\sum y_i$ =	$\sum x^2_i$ =	$\sum x^3_i$ =	$\sum x^4_i$ =	$\sum x_iy_i$ =	$\sum x_iy^2_i$ =
	1111	24.69	207075	38848879	7335565779	4549.75	18700.93

To minimize the sum of squares of the above wrong numbers

$$S = \sum_{i=1}^{n} v_i^2 = \sum_{i=1}^{n} (ax_i^2 + bx_i + c - y_i)^2 \to \min \quad (9)$$

In Eq. (9), a, b, and c must satisfy the system of equations

$$\begin{cases} \frac{\partial S}{\partial a} = 0 \\ \frac{\partial S}{\partial b} = 0 \\ \frac{\partial S}{\partial c} = 0 \end{cases} \Leftrightarrow \begin{cases} \frac{\partial S}{\partial a} = 2\sum_{i=1}^{n} (ax_i^2 + bx_i + c - y_i)\, x_i^2 = 0 \\ \frac{\partial S}{\partial b} = 2\sum_{i=1}^{n} (ax_i^2 + bx_i + c - y_i)\, x_i = 0 \\ \frac{\partial S}{\partial c} = 2\sum_{i=1}^{n} (ax_i^2 + bx_i + c - y_i) = 0 \end{cases} \quad (10)$$

Simplify the system of Eq. (10) to get the following system of equations

$$\begin{cases} a\sum_{i=1}^{n} x_i^4 + b\sum_{i=1}^{n} x_i^3 + c\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} x_i^2 y_i \\ a\sum_{i=1}^{n} x_i^3 + b\sum_{i=1}^{n} x_i^2 + c\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} x_i y_i \\ a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i + nc = \sum_{i=1}^{n} y_i \end{cases} \quad (11)$$

In the system of Eq. (11), x_i is the fuel injection pressure, and y_i is the soot emission corresponding to each point x_i shown in Table 4.

Solve the system of Eq. (11), and find the coefficients a, b, and c. Substitute the values of a, b, and c into the function of $y = ax^2 + bx + c$ to determine the experiment function.

$$y = 0.0001x^2 - 0.061x + 11.27 \quad (12)$$

The above function represents the mathematical relationship between soot emission and fuel injection pressure. Therefore reflecting soot emission characteristics according to fuel injection pressure. However, to evaluate the reliability of the found function, it is necessary to use the coefficient of determination R^2

$$R^2 = \frac{\hat{\beta}_2^2 \sum_{i=1}^{n} x_i^2}{\sum_{i=1}^{n} y_i^2} \tag{13}$$

With: $$\hat{\beta}_2 = \frac{\sum_{i=1}^{n} y_i x_i}{\sum_{i=1}^{n} x_i^2} \tag{14}$$

The property of the coefficient R^2 will indicate whether the empirical function form is appropriate or inappropriate, reliable or not.

The calculated results have $R^2 = 0.9652$, which shows that the variation law of experimental results has the form according to the function found.

Eq. (12) can be applied to adjust the injection pressure for engines with similar parameters to the research engine to reduce soot emissions shown in Figure 9 when the injection pressure drops to 166 bar leading to low combustion efficiency, which increases soot emissions by up to 20%.

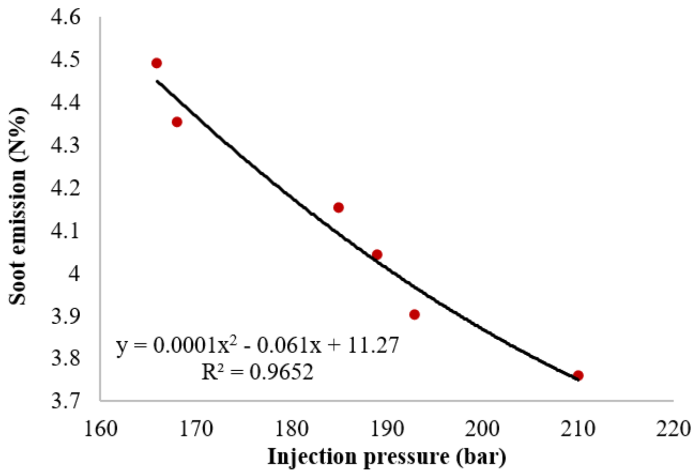


Fig. 9. Soot emission according to the injection pressure

4. Conclusion and Future Work

Based on simulation results, the fuel injection pressure is reducing, causing the spray structure to decrease, and the formation of the combustion mixture in the combustion chamber is uneven, which increases the formation of soot.

Experimental results when adjusting the injection pressure decreased, the soot emission content increased because the soot measured after the exhaust valve is the difference between the amount of soot formed with the amount of soot oxidized when the mixture The air-fuel is uneven, the combustion temperature is low, leading to poor oxidation, which also increases the soot emission of the engine.

In this study, when the amount of soot increased to 20% compared to the initial state in the condition that the group encloses the combustion chamber and the fuel is stable, only the injection pressure is reducing, so checking the fuel injection system is necessary. Eq. (12) is a function that represents the mathematical relationship between soot emission and fuel injection pressure.

Therefore, it is possible to measure the value of injection pressure and soot emission before the engine operated to compare with the data after the engine work time, which will assist in diagnosing the technical state of the machine effectively, mainly the fuel injection system, to determine timely and effective repair and maintenance measures.

The simulation and experimental study of the effect of the pressure drop at the end of the compression stroke on the formation of the combustion mixture and exhaust gas emissions of the diesel engine used as the main engine of the fishing vessel.

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