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Adoption of the F-statistic of Fisher-Snedecor distribution to analyze importance of impact of modifications of injector opening pressure of a compression ignition engine on specific enthalpy value of exhaust gas flow

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This article analyzes the effect of modifications of injector opening pressure on the operating values of a compression ignition engine, including the temperature of the exhaust gas. A program of experimental investigation is described, considering the available test stand and measurement capabilities. The structure of the test stand on which the experimental measurements were conducted is presented. The method of introducing real modifications of injector opening pressure to the existing test engine was characterized. It was proposed to use F statistic of Fisher-Snedecor (F-S) distribution to evaluate the importance of the impact of modifications of injector opening pressure on the specific enthalpy of the flue gas flow. Qualitative and statistical studies of the results achieved from the measurements were carried out. The specific enthalpy of the exhaust gas for a single cycle of the compression ignition engine, determined from the course of rapidly variable flue gas temperature, was analyzed. The results of these studies are presented and the usable adoption of this type of assessment in parametric diagnosing of compression ignition engines is discussed.

Key words: *diagnosis, injector opening pressure, F statistic of the Fisher-Snedecor distribution, compression ignition engine, exhaust gas temperature*

1. Introduction

The opening pressure of the injector p_{inj} is a parameter that significantly affects the combustion process and heat release in a compression ignition engine [2]. It affects the operational parameters of the engine, and also emissions of harmful and toxic ingredients of exhaust gas. The necessity of parametric assessment based on rapidly variable flue gas temperatures is due to the limited controllability of marine engines (there are no indicator valves) with the concomitant requirement to measure exhaust gas temperatures [9–11, 20–22]. The thermal and flow processes occurring in such engines are comparable to the ones in the single-cylinder research engine. Therefore, it was proposed to make diagnostic deductions about the functional state of the fuel supply system of a compression ignition engine based on observations of rapidly varying flue gas temperature in the exhaust duct. For this purpose, F statistic of F-S distribution was used, which makes it allowed to assess whether the opening pressure of the injector p_{inj} significantly affects the specific enthalpy of the exhaust gas flow h_{exh} averaged for a single engine cycle, identified on the basis of the quickly varying temperature of the flue gas of a compression ignition engine.

2. The impact of injector opening pressure modifications on exhaust gas temperature

One of the major quantities influencing the quality of combustion of fuel in a compression ignition engine and the composition of the exhaust gas is the opening pressure of the injector p_{inj}. Too low pressure p_{inj} results in disturbances in the combustion process, for example, in the form of increased maxima in the combustion process: pressure and temperature [17]. On the other hand, too high p_{inj} causes, for example, "hard" engine operation, resulting in excessive dynamic forces of the piston-crank mechanism. Measurement of the rapidly fluctuating temperature of the flue gas can allow to detection of the state of fractional fitness or operational unfitness of the engine, resulting from an increased or decreased value of p_{inj}.

2.1. Defectiveness of the injection system of a compression ignition engine

Compression ignition engines, which are the main propulsion system of ships as well as their electric power plants, generate operating costs that account for more than 70% of the cost of maintaining the overall power plant on a ship, mainly due to the high prices of fuels and lubricating oils [29]. There is a strong relationship between engine reliability and ship safety. Taking into account these two aspects – shipping safety and ship operating costs – diagnostic methods and devices are being developed mainly with the reliability of ship engines in mind. However, keeping in mind that it has a very complicated structural construction, it is necessary to carry out its logical decomposition into functional systems, components and elements to determine the depth of the diagnosis to be made. A schematic representation of the division of the structural design of a marine engine into appropriate levels, according to the increasing detail (depth) of the classification of the technical condition carried out – Fig. 1. The last element of the subject of diagnosis is considered indivisible [17].

Statistics show that marine engines are the most unreliable machines on a ship [29, 30]. Among the most common damages, those affecting low-speed engines account for 38% of the total number of damages, while medium-speed engines account for 15.7% of all accidents considered.

Analyzing the failure of marine engines, regardless of their purpose, essential functional systems should be considered: the fuel supply system (almost 50% of all damages) and working medium exchange system (24.7%). For the fuel supply system, injectors (41%) and injection pumps (38%) are the components usually fail [29].

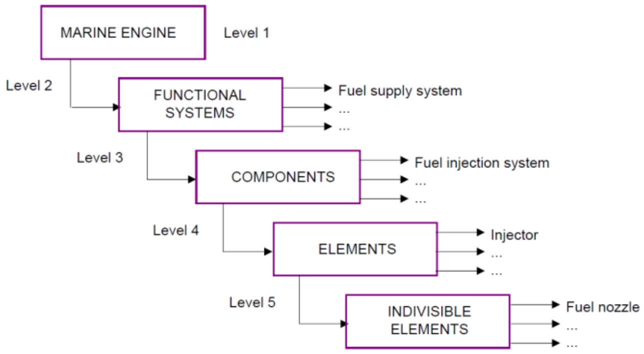


Fig. 1. Schematic of the decomposition of a marine compression ignition engine

Authors prove in their statistical studies that injectors are the most unreliable elements in all components of the fuel supply system of marine engines. Bruski, in his doctoral dissertation, presented the results of statistical studies collected at the Naval Academy's Institute of Ship Construction and Operation for medium-speed engines operated on Navy ships [4]. The author indicates that malfunctions were occurring with the highest incidence in the following functional systems: fuel supply (72%), valve train (19%), and air supply (9%). While 54% of injector breakdowns occurred in the fuel supply system, they represented 38.9% of all malfunctions of marine engines in operation.

The problem of the reliability of structural elements that are part of the functional systems of a marine piston engine was also studied by a scientific team from Vietnam consisting of Ta et al. [28]. The authors of the publication point to the main and auxiliary engines as the components of a marine ship's engine room and electric power plant that are most often damaged, while generating the highest costs from insurance and repairs. Of the authors' analysis of 558 failures of the main marine propulsion units (main and auxiliary engines, reduction gears, utilization boilers, propeller shafts and others), 41.6% involved main engines and 21.5% involved auxiliary compression ignition engines. The authors described the injection system is the one of all marine engine components that are wearing out most rapidly – every additional 500 hours of engine running doubles the probability of failure of this system's components.

The issue of reliability of marine IC engines was also dealt with by Czajgucki [5]. On the basis of the data collected on their damage statistics, he showed that the injectors are the component of the engines studied that is most often damaged (more than 60% of all the components analyzed by the author), primarily due to the low quality of the marine fuel used. The proportions of damages to each of the elements included in the systems of CEGIELSKI-SULZER type 6RD68 engines with a power of 5.5 MW are shown in Fig. 2. The graph was created on the basis of the courses of the reliability functions of injectors, injection pumps, starting valves, piston rings, cylinder liners, pistons and heads of 6RD68 engines supplied with residual marine fuel, which have worked 1500 hours.

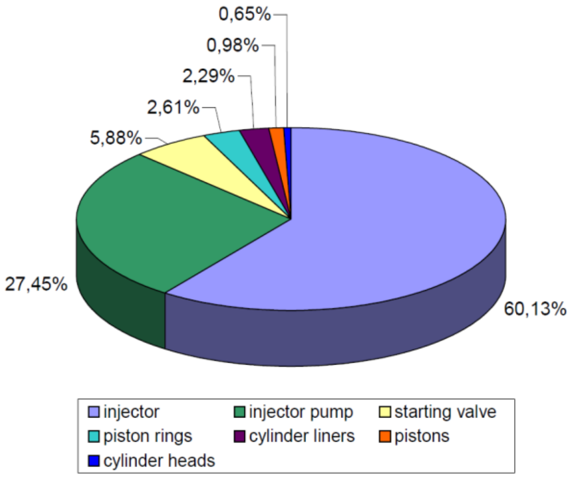


Fig. 2. Percentages of damage to individual structural elements of CEGIELSKI SULZER engines type 6RD68 with a power of 5.5 MW

The most common damage to injectors is primarily due to the extreme adverse conditions of high fuel pressures and, in the case of the nozzle itself, additionally high and variable temperatures of the working medium in the combustion chamber [4, 8, 13, 27]. As a consequence, the injector leaks, the opening pressure drops relative to the reference pressure, and the precision pair is excessively degraded [30]. The most common nozzle failures include the complete or fractional loss of clearance of the nozzle holes, deformation of the shape and change in geometric dimensions ("recalibration") of these holes as a result of erosive and thermal wear, leakage of the seating of the pin, or stuck pin in the guideway.

The following factors affect the technical condition of the injector:

– erosive and corrosive effects of various types of impurities contained in the fuel, e.g. particulate matter, water, vanadium, sulfur – in the case of non-sulfurized fuels or so-called "cat fines" – for low-sulfur residual fuels
– the propensity of low-quality fuel to form carbon build-ups and lakes
– overheating of the injector due to disruption of its cooling process.

In newly produced low-sulfur residual fuels, impurities in the form of hard, lightweight and difficult to remove aluminum and silicon oxide particles – so-called "cat fines" – are often present. These can lead to serious damage to components of the engine's functional systems, as a result of the abrasive effects present in the unpurified fuel in the form of catalytic fines. It is a byproduct of the catalytic hydrocracking process [15, 16]. The fuel atomizer itself can also suffer this type of mechanical damage, as can be seen in Fig. 3 [1].

In the case of the injector spring, due to operation at high temperatures and pressures, over time wear occurs due to the loss of its own elasticity. The result can then be a reduced injector opening pressure, causing combustion interference [17].

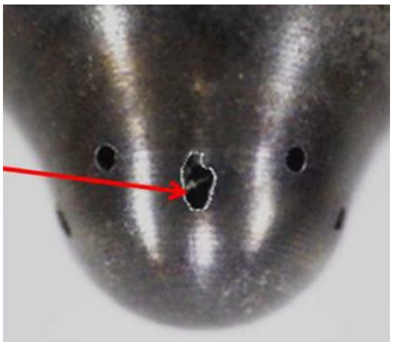


Fig. 3. Destroyed marine engine fuel nozzle due to destructive effects of catalytic fines [1]

Modifications of the opening pressure of the injector p_{inj} usually occur as a result of changes in the spring's own elasticity (adjusted by shims under the spring), and also as a result of leaks in the injection pump [3, 7, 14, 26, 29].

It should also be kept in mind that when the working process of an engine is disturbed, its heat loads increase, so any malfunctions that aggravate the engine and/or its associated systems can result in heat overload. The engine systems affecting the increase in heat loads are considered to be, in order: the fuel supply system, the supply air system, the piston-ring-cylinder liner set, the cylinder liner lubrication system and the cooling system [29].

Analyzing the results of reliability studies on the functional systems of marine engines, it was decided to subject to experiment and statistical and merit analysis those failures that occur most frequently. In selecting the changes to be made to the structural design to reflect the states of operational unfitness allowed in an engine in use in real conditions, i.e. on a ship. The technical capabilities of the compression ignition research engine were also taken into account. Thus, the following damage was taken into account for the applied experimental plan:

- loss of air inlet duct clearance (reduced inlet air pressure), the analysis of which was presented in the paper [25]
- leakage of the combustion chamber (reduced compression ratio), discussed in the article [24]
- injector spring relaxation (reduced injector opening pressure), the results of which are presented in this paper.

2.2. Temperature of exhaust gas

There is a relationship between flue gas temperature and injector opening pressure, according to simulation and investigation studies conducted in this area. In the article [23], the author shows the analytical data from a numerical simulation of the working of a compression ignition engine. A laboratory Farymann Diesel type D10 engine was successfully implemented in the DIESEL-RK application. Chosen malfunction of its operational fuel supply system – cut down opening pressure of the injector p_{inj} – was implemented. One of the values of adequate diagnostic values was exhaust gas temperature T_{exh}. The variability runs of changes in the temperature of the flue gas T_{exh}, major discrepancies in the values of this value occur in area of maximum – Fig. 4. Cut down injector opening pressure p_{inj} from 12 MPa to 10 MPa caused an increment of exhaust gas temperature by about 10 K at the maximum value of T_{exh}. Discrepancy in amounts of flue gas temperatures T_{exh} for the two reviewed states is also visible for remaining part of the engine cycle, however it is lower.

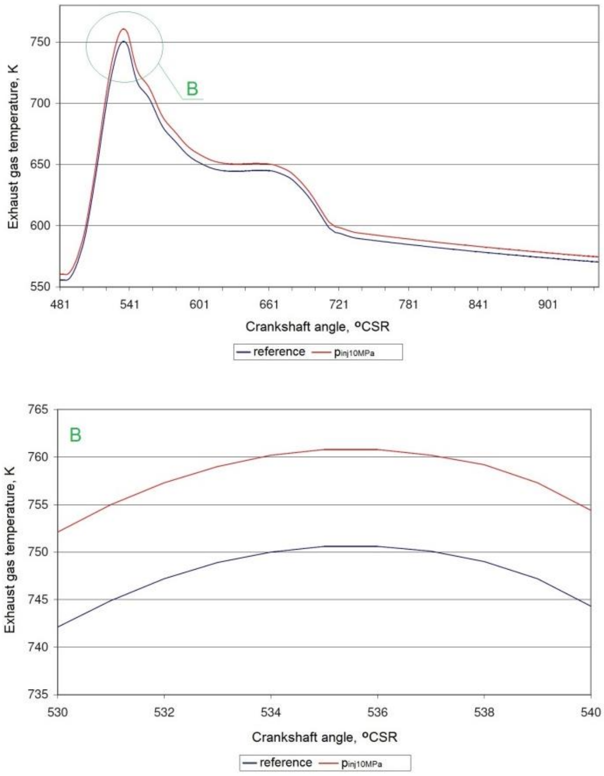


Fig. 4. Runs of changes in the temperature of the exhaust gas T_{exh} value for the crankshaft rotation angle, for portion of the engine operating cycle and for the region of existence of the peak value of the flue gas temperature, obtained by numerical simulation in the DIESEL-RK program for two values of injector opening pressure p_{inj} [23]

Experimental studies on, for among other things, the impact of injector opening pressure on exhaust gas temperature were carried out by the authors of the paper [19]. In these investigations, 2-butanol was added volumetrically to the diesel fuel and injector atomization pressures were modified. A single-cylinder, four-stroke and direct injection diesel engine was subjected to experimental tests on a direct current dynamometer. A 2-butanol-diesel fuel mixture was prepared by volumetrically adding 3% (B3 in Fig. 4), 5% (B5), 8% (B8) and 10% (B10) 2-butanol to regular diesel fuel (B0). The injection pressure of the injectors was set as 180 bar, 200 bar (originally), and 220 bar. The outputs of the experiment illustrate the comparison with standard engine operating conditions. Figure 5 shows the changes in flue gas temperature as a function of injection pressure for 2-butanol diesel mixtures. Exhaust gas temperature dropped for all additive fractions of 2-butanol versus pure diesel. The lower viscosity, density and cetane number result in worse in cylinder combustion and lower final combustion pressure and temperature, also flue gas temperature. Exhaust gas temperature dropped at 200 bar injection pressure, but not as much as at 180 bar. But the largest decrease is observed at 220 bar. Note, however, that increasing the injection pressure reduces the diameter of the fuel particles and upgrades the fuel's ability to diffuse into the combustion chamber. Greater diesel and 2-butanol mixtures spraying capacity immediately consume more energy from air in combustion chamber for evaporation, thereby cooling the cylinder and lowering the temperature of the final combustion and flue gas. However, regardless of the composition of the fuel tested, the impact of fuel injection pressure on exhaust gas temperature is noticeable.

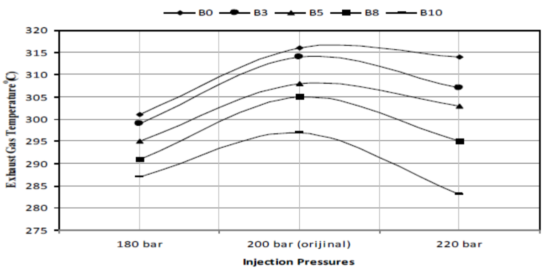


Fig. 5. The impact of injection pressure on exhaust gas temperature [19]

Studies by other authors have investigated the performance evaluation of a low heat rejection (LHR) combustion chamber engine with an air gap insulated piston and an air gap insulated liner when operating on clean diesel fuel with varying injector opening pressures [12]. Operating values (brake thermal efficiency, exhaust gas temperature, coolant load, volumetric efficiency, sound level) and exhaust emissions (particulate matter and nitrogen oxide emissions) were specified at different values of the engine's mean brake effective pressure (BMEP). The authors prove that the engine with the LHR combustion chamber upgraded performance at 80% of full-load operation and continued to increase with increasing injector opening pressure. In Table 1, we can see that the flue gas temperature (EGT) dropped slightly with increasing injector opening pressure in diesel operation. This was due to upgraded fuel-air ratios with better atomization characteristics.

Table 1. Variation of performance parameters with injector opening pressure with Diesel operation; BTE – brake thermal efficiency, BSFC – brake specific fuel consumption, EGT – exhaust gas temperature, VE – volumeric efficiency [12]

Parameter/unit	Conventional engine			Engine with LHR combustion chamber		
	190	230	270	190	230	270
Peak BTE [%]	28	29	30	29	30	30.5
BSFC [kg/kW·h]	0.34	0.33	0.32	0.35	0.34	0.33
EGT [°C]	425	410	395	475	450	425
Coolant load [kW]	4.0	4.2	4.4	4.5	4.2	3.8
VE [%]	85	86	87	79	80	81
Sound levels [dB]	85	80	75	90	85	80

3. Investigation on experimental compression ignition engine in the conditions of actually implemented modifications of the injector opening pressure

Identifying of the impact of dropped injector opening pressure on engine running is allowed through investigational research. Incidence imitation of the state of fractional serviceability by actually implemented modifications of p_{inj} makes it possible to register chosen control values under these requirements. Exhaust gas temperature gives a diagnostic measures and enables a determination of the impact of the modified injector opening pressure on the specific enthalpy of the flue gas. Nevertheless, it is necessary to be mindful of suitable statistical and mathematical treatments tools in order to maximize the diagnostic reporting of flue gas temperature.

3.1. Overview of laboratory bench and applied testing equipment

Measurements were conducted on a laboratory bench test of a four stroke, a single cylinder engine Farymann Diesel engine type D10 (Fig. 6), situated in the Laboratory of Marine Power Plants, Faculty of Mechanical Engineering and Ship Technology, Gdansk University of Technology. Main data specifications of the engine are these:

– power nominal value 5.9 kW
– rotational speed nominal value 1500 min^{-1}
– torque nominal value 38 N·m
– diameter of cylinder 90 mm
– piston stroke 120 mm
– compression ratio 22:1
– volume of cylinder stroke 765 cm^3.

The design solution of the Farymann Diesel type D10 research engine makes it allowed to minimize the delay of self-ignition of fuel, approximating the combustion process to the process of isochoric heat input in the preliminary combustion chamber and the process of isobaric heat input in gas volume space over the piston (major combustion chamber) with a significant greater displacement. Both chambers are joined by a narrow flow (turbulent) duct, which, for one thing, offers ideal environment for studying the fuel combustion procedure in the pre-chamber (dynamics of pressure changes, thermal emission and self-ignition capability of the feed fuel), and, for another, reduces the mechanical and thermal load in the major combustion chamber coupled straight to the piston-crank mechanism. In addition, in the pre-chamber, although a straight (reliable) spigot injector is used, very good conditions for complete combustion of the fuel are achieved. Also, the engine is at a lower susceptibility to burning fuels with low auto-ignition ability. Disappointingly, this comes at the cost of a large reduction in the effectiveness of the implemented operating process, primarily because of the hydraulic losses of the return flow of the working medium through the chamber connecting channel, and also higher heat losses raised by the coolant from the walls of the expanded combustion chamber.

During the tests, the following engine control values were recorded:

– exhaust gas pressure and temperature
– current of generator (motor) load
– voltage at generator armature terminals
– piston top dead center signal
– outlet valve opening signaling.

It is presented in Table 2 with a synthesis of the tested control values measured and the sensing equipment which was used in the tests.

A DT-9805 type multifunction recording and measuring module was used to record the fast variables: temperature and flue gas pressure, and the top dead center piston signal. Matlab software was used to save the measured data. The test results presented are the mean of 90 successive measurements registered at the same engine working conditions defined by engine load, speed of the crankshaft and environmental values. Throughout the experiments, the engine burned MGO-type marine fuel. During the entire test, the crankshaft rotational speed was kept constant at 1442-1444 rpm. The sampling frequency was about 7000 Hz.

3.2. Experimental investigations agenda

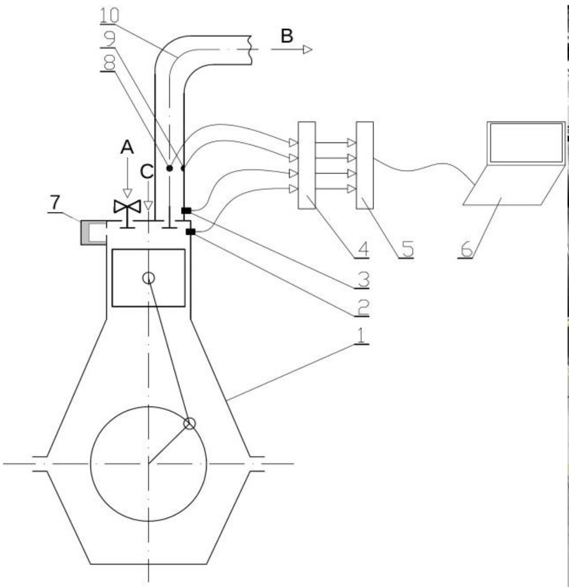
Within the study conducted by the present article's author, the main objective was determining the informability of the diagnostic value, which is the rapidly varying flue gas temperature of a compression-ignition engine, as a function of actual modifications of chosen values of its structural design. A randomized static and complete experimental scheme was used [18]. Presented in the current article is a portion of results of a broader program of conducted studies: the impact assessment of the injector opening pressure on the specific enthalpy of the test engine's flue gas. According to this, it is therefore feasible to apply the results of laboratory tests to full-size marine engines for diagnosis inference.

Laboratory tests were conducted on a Farymann Diesel type D10 engine. The object of the study of thermal-fluid processes was determined through the structural elements that limit the working space of the cylinder, as well as the injection system. In the conducted investigations and analyses, the processes taking place in the in-cylinder volume have not been dealt with, but only the rapidly varying flue gas temperature signal registered in the flue gas duct. Diagnostic measures were determined from the registered rapidly varying flue gas temperature report signal, but this article only discusses the specific enthalpy of the average flow of flue gas in a single cycle of a compression-ignition engine – h_{exh}.

Table 2. The values of the Farymann D10 a single cylinder compression ignition engine measured on the laboratory bench

Item	Value	Measuring device	Unit	Measurement range
1.	Exhaust gas temperature – T_{exh}	Type K welded thermocouple with 0.5 mm outer diameter connector, manufactured from inconell	^{o}C	0–1000
2.	Exhaust gas pressure in the exhaust duct – p_{exh}	Optical pressure sensor – Optrand C12296	V	0–689475.73 Pa (0–100 psi), sensitivity $6.01\cdot10^{-8}$ V/Pa (41.43 mV/psi)
3.	Engine speed (angular position – CA) – n Top dead center – TDC	Induction engine speed sensor and TDC sensor	min^{-1}	0–3000
4.	Current of generator (motor) load – I_{gen}	Electric current meter	A	0–15
5.	Voltage at generator armature terminals – U_{gen}	Voltmeter	V	0–250
6.	Outlet valve opening signaling	Gap type opto-isolator with a comparator LM393	V mm	0–5 10 (gap)

a)



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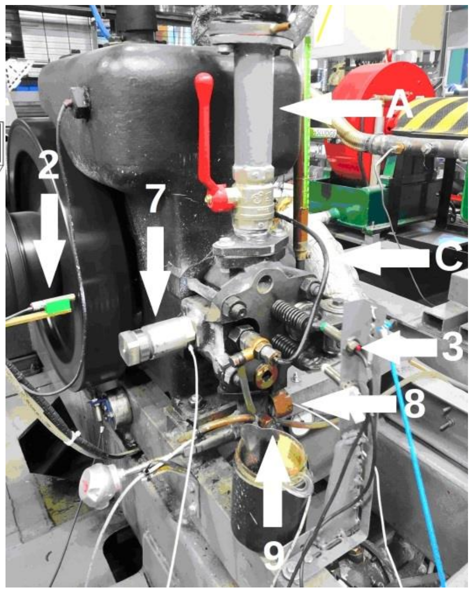

Fig. 6. a) Schematic of the bench with detectors installation points indicated as: 1 – Farymann D10 engine, 2 – TDC and engine speed sensor, 3 – outlet valve opening sensor, 4 – A/C converter, 5 – data recorder, 6 – analysis software, 7 – element that enlarges the capacity of the combustion chamber, 8 – pressure sensor, 9 – thermocouple in the water jacket, 10 – exhaust gas duct, A – intake air, B – exhaust gas, C – fuel line

b) Visual image of laboratory bench with indicated locations of sensors for registered values: 2 – TDC and engine speed sensor, 3 – outlet valve opening sensor, 7 – element that enlarges the capacity of the combustion chamber, 8 – pressure sensor, 9 – thermocouple in the water jacket, C – fuel line

In steady states, three characteristics of a compression ignition engine's operation are allowed. In the conducted studies, the regulator characteristics were applied, with a variable speed within the scope of astatic operation of the controller. During the experimental investigation conducted on a Farymann Diesel type D10 engine, measurements were carried out for 3 operating points according to the regulator characteristics – Table 5.

In this stage of investigation and mathematical processing and statistical analysis, modifications were made to the structure's parameter of injector spring tension through appropriate selection of shims. In this way, its relaxation lowering the opening pressure of the injector was simulated. In the engine under test, was installed an injector with shims with a thickness of δ_{inj} equal to 2.3 mm in sum, causing a fuel injector opening pressure of about 12 MPa (the value for the reference condition). During the test for condition 3, shims with a total thickness of 1.8 mm were mounted in the injector, resulting in a reduction of the injector opening pressure to 10 MPa, which simulated a failure of the fuel injection system involving too early injection of fuel into the combustion chamber – Fig. 7.

Fig. 7. Preview of injector parts which were used in the tests, among them exchangeable (adjustable) shims under the injector spring

During a diagnosis study of an engine under steady-state conditions, diagnostic values are determined from among its output values. Those are selected that respond more strongly to changes in the values of structural quantities than to changes in the values of input quantities, forcing an ongoing work process. Comparing the susceptibilities of multiple control values, in various units, requires taking the relative values of input, output and structural values for this study [17]. The null hypothesis used in the study assumes no influence of the input parameter on the output parameter. The impact of an input parameter is important if the calculated value of the applied statistic is equal to or greater than the critical value, given in the tables for the adopted significance level α and the number of freedom degrees f = n – 1. The conditions for the application of one-sided parametric tests were met, so an F statistic with an F-S distribution was adopted [6, 18]. It was assumed that the results of measurements of all control quantities can be modeled as random variables with a specified expectation value and variance and normal distribution, the variances of the random variables are equal or close in value, and the parametric tests used have a one-sided critical area. The chance of an error of first kind, involving an assumed significance level α, and the possibility of an error of second kind, with a value of β = 1 – α, were taken into account.

Table 3 shows the matrix of an operational testing program, in this case a randomized static plan, enabling to assess the significance of the effect of the opening pressure of the injector p_{inj} realized within a certain range of variation, on the determined output factor, which is the specific enthalpy of the flue gas flow in the range of one duty cycle – h_{exh}.

Table 3. Matrix of experimental investigation program – static randomized complete plan

Input factor level	The number of experience		
	1	...	4
p_{inj1}	h_{exh11}	...	h_{exh41}
p_{inj2}	h_{exh12}	...	h_{exh42}

In addition, once a factor is considered significant (F_{cal} > F_{cr}), it is allowed to compare the difference $\Delta F = F_{cal} - F_{cr}$ for particular diagnosis measures. That enables an assessment of precisely whose diagnostic measures are more highly affected by the input parameter (for example, structures) – the greater the ΔF, the greater the impact there will be.

3.3. Statistical analysis results for variable injector opening pressure p_{inj}

Outgoing factor amounts, being the specific enthalpy of the flue gas per each cycle of engine operation, for three engine steady-state power conditions, are shown in Tables 4a–c. The points P_1, P_2 and P_3 defined by values are due to the adopted performance steering characteristics of the engine.

In order to determine the value of the F_{obl} statistic, the following null hypothesis was set:

H_0: the value of the injector opening pressure has no impact on the value of the specific enthalpy of the exhaust gas flow mean within a single engine cycle ($S_{II2} = S_{I2}$).

Based on the numerical data summarized in Tables 4a–c and the adopted importance level α = 0.05 and based on the right-hand critical zone scenario, the specific enthalpy of the flue gas flow in a single engine cycle was calculated for every test point (P_i), with the number of degrees of freedom for the numerator and denominator (f_1 = 1 and f_2 = 6). Then the critical value of the F_{cr} = F(0.05;1;6) = 5.9874 statistic was read from the statistical tables [17], and the values of F_{cal} were determined, the values of which are shown in Table 5. When evaluating the influence of the mean within a single cycle of the specific enthalpy of the exhaust gas stream h_{exh}, it (specific enthalpy) has a significant impact ($F_{cal} > F_{cr}$) only at point 3 of the engine's control characteristics.

Based on the results of the statistical analysis – Table 4 and 5, and the prepared characteristics of the variation of the specific enthalpy of the exhaust gas flow h_{exh} – Fig. 8, in the considered range of set load variation and the value of injector opening pressure, it can be concluded that the statistical a single-factor analysis unambiguously showed that the injector opening pressure has no important impact on the specific enthalpy of the exhaust gas stream in load states 1 and 2 according to the engine's control characteristics, while in state 3 the effect of this diagnostic parameter was significant (ΔF = 9.06). Therefore, it was considered that the two-factor analysis would not take into account the injector opening pressure as a factor affecting the specific enthalpy of the flue gas stream within a single engine cycle. From the characteristics shown in Fig. 8, it can be deduced that lowering the injector opening pressure results in a decrease in the specific enthalpy value of the exhaust gas. This decrease is greater if the engine load is higher.

Table 4a. The value of the mean within a single cycle specific enthalpy of the exhaust gas h_{exh} for variable values of injector opening pressure p_{inj} at a point P_1

	Load point 1 (432 W; 5.1 A; 72 V)					
Input parameter	Value, MPa	Number of experience				
		1	2	3	4	y_i
p_{inj1}	12	12.1299	12.1986	12.2763	12.2176	12.2056
p_{inj2}	10	12.2516	12.2652	12.0890	11.8609	12.1167

Table 4b. The value of the mean within a single cycle specific enthalpy of the exhaust gas h_{exh} for variable values of injector opening pressure p_{inj} at a point P_2

	Load point 2 (768 W; 6.8 A; 96 V)					
Input parameter	Value, MPa	Number of experience				
		1	2	3	4	y_i
p_{inj1}	12	13.8992	13.6571	13.4404	13.3947	13.5979
p_{inj2}	10	13.3819	13.3464	13.2356	13.2772	13.3103

Table 4c. The value of the mean within a single cycle specific enthalpy of the exhaust gas h_{exh} for variable values of injector opening pressure p_{inj} at a point P_3

	Load point 3 (1200 W; 8.5 A; 120 V)					
Input parameter	Value, MPa	Number of experience				
		1	2	3	4	y_i
p_{inj1}	12	15.4712	15.4883	15.3075	15.3299	15.3992
p_{inj2}	10	15.0728	15.1370	14.8994	14.6505	14.9399

Table 5. The value of statistics F_{cal} and ($\Delta F = F_{cal} - F_{cr}$) for cut down injector opening pressure p_{inj} and its impact on h_{exh}

Point according to regulator characteristics	F_{cal} and ($\Delta F = F_{cal} - F_{cr}$) for h_{exh} [kJ/kg]
P_1 (432 W; 5.1 A; 72 V)	0.81 (–5.18)
P_2 (768 W; 6.8 A; 96 V)	5.72 (–0.27)
P_3 (1200 W; 8.5 A; 120 V)	15.05 (9.06)

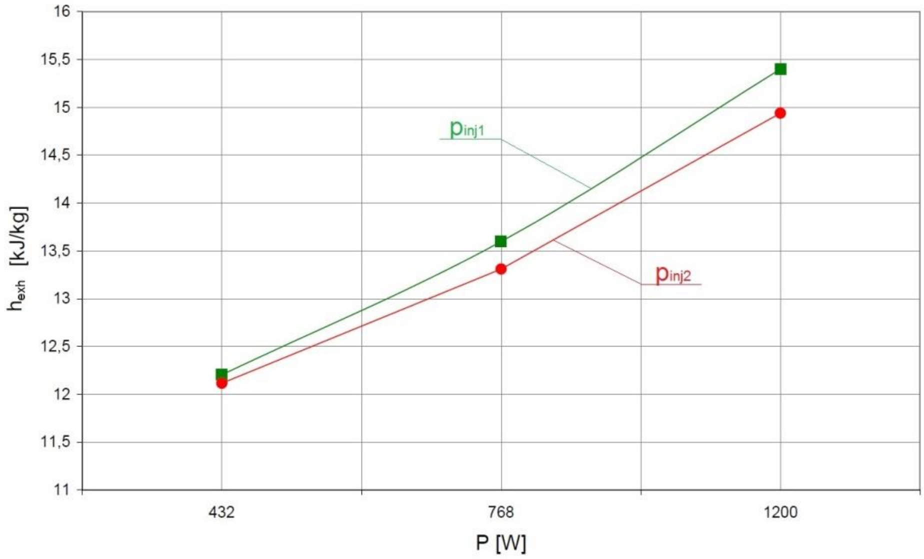

Fig. 8. Effect of the injector opening pressure on the value of the mean within a single cycle of the exhaust gas enthalpy $h_{śr}$ for compression ignition engine loads according to the regulator characteristics

4. Comments and final conclusions

The opening pressure of the injector p_{inj} is significant amount characterizing the operation of a compression ignition engine. It is a parameter that often accompanies damage to the injection system. Thus, it should be alarming to the engine user if it increases or decreases, indicating appearance of a status of partial utility or malfunction. Measurement of the quickly varying exhaust gas temperature makes it allowed to determine the impact of a modification in the input p_{inj} on a diagnostic measure such as h_{exh} only for a loaded engine (above 20% of the engine's nominal load). Then it is allowed, thanks to the use of a statistical instrument such as F statistic of F-S distribution, to determine the significant effect of p_{inj} on h_{exh} in the studied scope of engine load changes. The applied investigation and analytical method was considered effective for assessing impact of importance of modifications of input factor – structure (p_{inj}) on output value (h_{exh}). It is also allowed to determine other diagnostic measures on basis of rapidly changing exhaust gas temperature and determine impact of p_{inj} on it, thanks to use of F statistics. At the same time, this input value was eliminated in two-factor analysis, analyzing simultaneous impact of injector opening pressure and engine load on the specific enthalpy of the flue gas of a compression ignition engine.

Nomenclature

BTE	brake thermal efficiency
BSFC	brake specific fuel consumption
EGT	exhaust gas temperature
f	number of degrees of freedom for the numerator and denominator
F	statistic of Fisher-Snedecor distribution
H	hypothesis
I_{gen}	current of generator (motor) load
n	rotational speed value
p_{inj}	injection pressure
T_{exh}	temperature of exhaust gas
U_{gen}	voltage at generator armature terminals
VE	volumetric efficiency

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