Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

EFFECTS OF THE THERMAL ACTIVATION OF FUEL ON ENERGY PARAMETERS AND TOXICITY OF COMBUSTION GASES IN THE MARINE DIESEL ENGINE

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Abstract

This paper concerns theoretical basis of the influence of temperature of fuel on its main parameters, which affect the efficiency and toxicity of combustion gases in the marine diesel engine. It also presents the results of own research, carried out on a single-cylinder test engine on the engine test stand. These researches aimed to determine the efficiency of applying the thermal activation of fuel to improve energy and ecological properties of the engine. Heating of fuel up to 150^{o}C for the various values of torque and engine speed was applied. The test results indicated generally beneficial influence of fuel heating on the energy indexes and the decrease of exhausts emission.

1. Introduction

More and more restrictive legal regulations make severe requirements about the emission of toxic compounds from piston combustion engines and it is necessary to apply different methods of reducing these emissions to the permissible level. Significant group of methods reducing level of emission of those compounds in exhausts constitute the methods directly affecting the combustion processes, which are the main source of the toxic compounds. [1]

This group contains the conception of thermal activation of injected fuel, which consists in heating up fuel before it is injected to the combustion chamber. Such heating of fuel in assumption should accelerate the evaporation of fuel, and just ahead the cylinder it should initiate the destruction of nuclear bonds in hydrocarbon molecules that fuel contains, which in consequence will shorten the time of self-ignition delay and limit the amount of injected and prepared to combust fuel. In consequence, both speed of combustion just after self-ignition and size of the post flaming zone increase, which should result in the decrease of temperature in that zone. Due to the significant relation between the temperature and the nitrogen oxides formation, lowering the temperature at that zone will definitely decrease the intensity of these compounds formation and their emissions to the atmosphere. [2].

In the view of the influence of temperature on fuel properties, the most important physical values of fuel are viscosity, density and surface tension. These values affect in the significant extend on a course of fuel injection, but mostly they affect the volumetric change of fuel pumped in the injection pipe. This leads to the change in injection pressure and, in consequence, some modifications in the place of injector opening. Changes of the physical and chemical properties of fuel cause further effects, such as modification of time of injection, range of the fuel stream, and angle of fuel pulverization.

Empirical dependence [3] describes the relation between *dynamic viscosity* μ_{pal} [Pas], fuel temperature t_{pal} [^{o}C] and pressure P [bar]:

$$\mu_{pal}\left(P,t_{pal}\right)=\mu_{pal(20)}\left(\frac{20}{t_{pal}}\right)^{k}e^{B\cdot P} \quad (1)$$

where: k – temperature coefficient; k = 0,73,

B – pressure coefficient; B = 10^{-3}.

Having known the values of $\mu_{pal}\left(P,t_{pal}\right)$ and $\rho_{pal}\left(P,t_{pal}\right)$, which depend on pressure and temperature, it is possible to describe kinetic viscosity, also depending on these two parameters:

$$\nu_{pal}\left(P,t_{pal}\right)=\frac{\mu_{pal}\left(P,t_{pal}\right)}{\rho_{pal}\left(P,t_{pal}\right)}\left[\frac{m^2}{s}\right]. \quad (2)$$

Rapid decrease in both dynamic and kinetic viscosities of fuel along with the temperature increase occurs in the range of 50÷100°C. Then the rate of decrease is lesser.

Therefore, it can be stated that the viscosity determines the values of resistance of fuel flowing through conductors, filters, calibrated jets of pulverizator, and also the course of process of pumping and dosing the fuel and process of lubricating mobile elements of the injection system.

Density is a characteristic feature of every group of fuel, including Diesel fuel. The decrease in density and viscosity of fuel causes the decrease in engine power, a volumetric increase in unit fuel consumption and change of the amount of toxic compounds in exhaust gases. Density of fuel (Diesel fuel) is also a significantly changing parameter along with the change of temperature. At higher temperatures, the density decreases, according to the linear dependence given in literature [2].

Surface tension has a direct influence on the size of injected fuel droplets. Mean diameter of fuel droplets should be lesser at the higher temperatures, which facilitates the pulverization of droplets. Surface tension of hydrocarbon fuels depends on its chemical composition and it linearly decreases along with the increase of temperature and pressure.

Despite the development of mathematical models of combustion processes and production of toxic exhaust gases, they do not allow to define the influence of fuel temperature on these processes. Therefore, there is a need of conducting the research on engine test beds.

2. Own research

2.1. Organisation and course of research

The research was conducted in Naval Academy of Gdynia on the engine test stand on a 1-cylinder research test engine WOLA DMVa type, which technical parameters are presented in Table 1. In order to increase the temperature to the demanded level, there was prepared an appropriate heating system ahead the feed pump. Thermal energy used for heating was taken from another source, which was the calorimeter. Temperature of the injected fuel was measured in injected pipe just ahead the injector.

Table 1. Basic technical parameters of the engine

Type	Four-stroke, right-rotary
Cylinder Diameter	150 mm
Piston Stroke	180 mm
Engine speed	1500 rev/min

Nominal power (on the brake crank)	18 kW
Maximum torque	125 N·m
Unit fuel consumption at nominal power	185 g/(kW·h)
Compression ratio	15
Mean stroke speed	9 m/s
Pressure of the injector opening	21 MPa

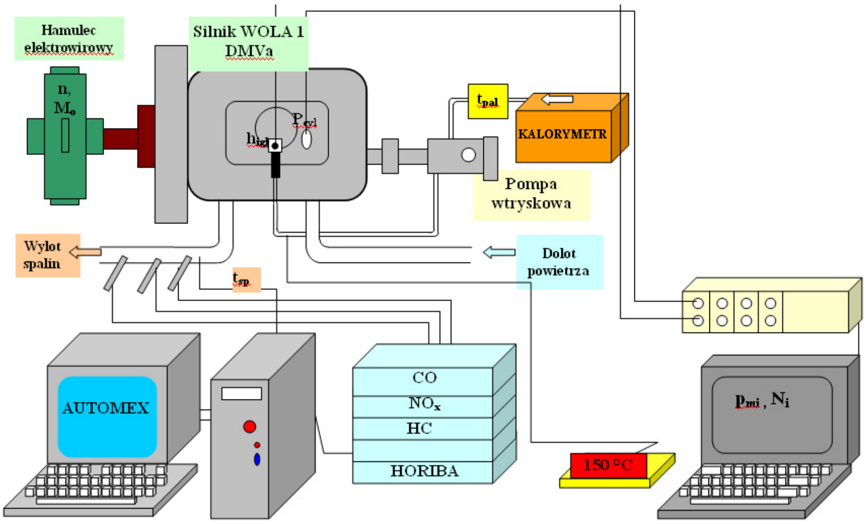

Fig 2. Scheme of engine measurement systems

Conducting the experiment, the theory of test planning was applied. Fig. 3 presents values that characterize the object of research.

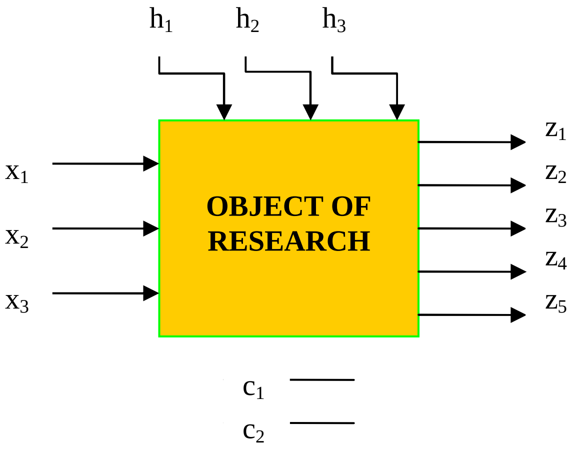

Fig 3. Model of the test engine WOLA (DMVa type), x - input values , z - output values, c-constant values, h- interferences

Among the above values, there were differentiated:

1. Set of input values X:
   - x_1 – temperature of fuel dosen to cylinder t_{pal} [°C];
   - x_2 – engine speed n [rev/min];

    - x_3 – torque T [N·m];
2. Set of output values Z:
    - z_1 – concentration of emitted carbon monoxide C_{CO} [ppm];
    - z_2 – concentration of emitted nitrogen oxides C_{NOx} [ppm];
    - z_3 – concentration of emitted hydrocarbons C_{HC} [ppm];
    - z_4 – mean indicated pressure p_{mi} [MPa];
    - z_5 – indicated power N_i [kW]
3. Set of values C, which can appear during the test, were accepted as constant (fuel type).
4. Set of interfering values H, which can be modified (ex. ambient temperature, atmospheric pressure, relative ambient air humidity).

Due to the low number of input values in the research, there was applied a complete three-valued 3^3 plan with 3 independent variables and 27 measurements carried out in a single measurement block. It is presented in Table 2. The scope of three fuel temperature values covered two extreme values, imposed by physical and chemical parameters of fuel as well as by the safety conditions during increasing the fuel temperature. The third value was the mean value of the two extreme temperature values. Other input values, such as engine speed and torque, were limited by the engine construction parameters. The extreme values and their arithmetical mean were accepted as in case of fuel temperature.

Table 2. Plan of the experiment 3** - fractal complete three-valued plan 1 block, 27 systems and received results of measurements

Number of measurement system	Input data			Output data				
	x_1	x_2	x_3	z_1	z_2	z_3	z_4	z_5
	t_{pal} [°C]	n [obr/min]	T [N·m]	C_{CO} [ppm]	C_{NOx} [ppm]	C_{HC} [ppm]	p_{mi} [MPa]	N_i [kW]
1	20	800	25	937.8	191.7	137.4	0.410	9.00
2	20	800	75	1079.3	208.9	173.9	0.577	12.67
3	20	800	125	3023.3	405.5	210.8	0.751	16.47
4	20	1000	25	654.6	206.4	118.5	0.381	10.41
5	20	1000	75	1320.8	247.9	182.1	0.573	15.68
6	20	1000	125	2801.9	287.0	202.7	0.756	20.69
7	20	1200	25	848.1	165.9	129.8	0.383	12.58
8	20	1200	75	1890.2	231.5	179.5	0.537	17.63
9	20	1200	125	2045.9	290.1	162.3	0.695	22.81
10	85	800	25	557.7	160.1	60.5	0.409	8.96
11	85	800	75	597.1	303.4	75.4	0.588	12.81
12	85	800	125	1261.7	444.8	111.5	0.767	16.79
13	85	1000	25	519.1	167.9	48.2	0.413	11.29
14	85	1000	75	943.4	269.0	133.2	0.587	16.11
15	85	1000	125	1663.9	423.45	127.8	0.789	21.54
16	85	1200	25	715.2	147.5	99.5	0.488	16.01
17	85	1200	75	1296.4	239.1	171.2	0.683	21.41
18	85	1200	125	1544.4	294.6	163.4	0.731	24.07
19	150	800	25	525.71	182.1	56.1	0.433	9.47
20	150	800	75	643.2	272.3	75.5	0.631	13.81

21	150	800	125	1242.3	442.9	126.5	0.801	17.57
22	150	1000	25	517.7	175.4	53.7	0.481	13.13
23	150	1000	75	828.9	278.2	80.9	0.626	17.11
24	150	1000	125	1693.4	378.1	93.5	0.849	23.22
25	150	1200	25	765.1	139.1	112.6	0.533	17.49
26	150	1200	75	1294.8	248.9	159.2	0.670	21.99
27	150	1200	125	1431.3	298.2	149.1	0.850	24.66

2.2. Statistical and content-related analysis of the test results

Registered parameters were statistically analyzed at confidence interval $\alpha = 0.05$. After performing analysis of match measures of the significant statistic coefficients, there was selected an interaction L-L (linearly-linear) that had the most beneficial values of the quotient of regression coefficient and mean error of estimation the regression coefficient $t = b_i/S_{bi}$.

For the accepted model there were plotted some graphs presenting the estimation of match effects and the influence of the respective input values on a considerate output value. The graph of standardised effects is an effective tool presenting which factors have the greatest influence on the output value. As an example, Fig. 4 shows the influence of fuel temperature on the concentration of HC in exhaust gases.

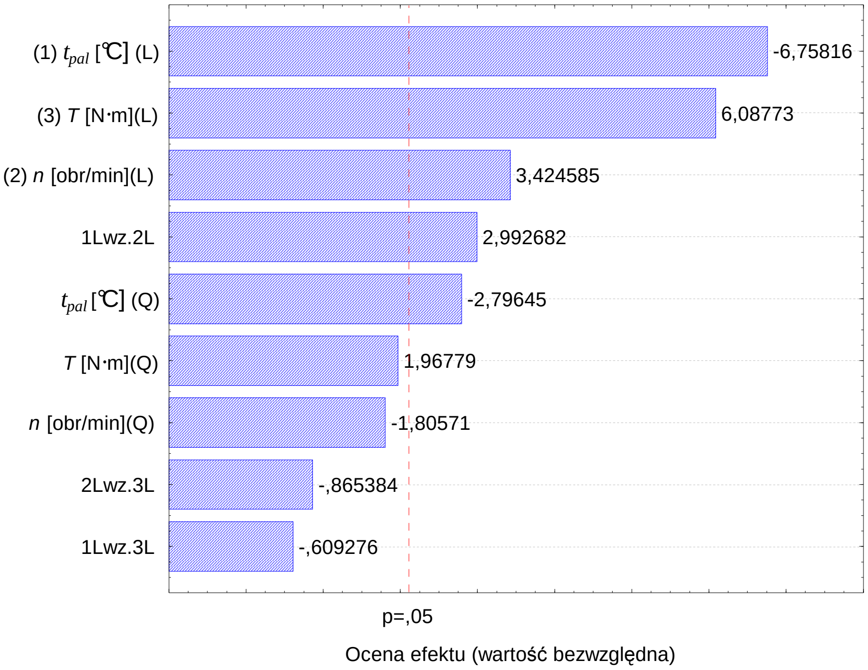

Fig 4. The graph of the standardised effects of HC concentration in an outlet manifold of the engine tested

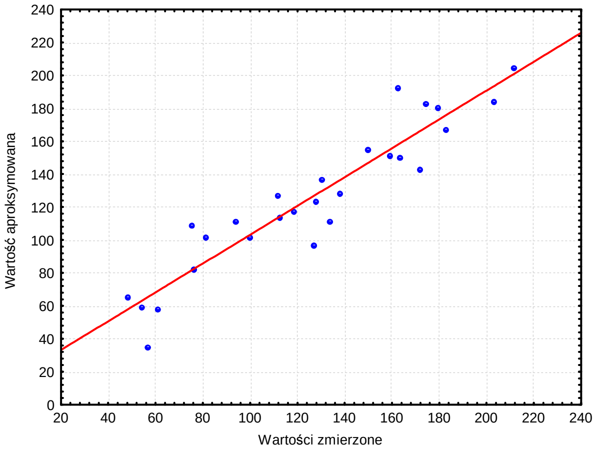

Fig 5. Dependence of the measured and approximated values of HC concentration in an outlet manifold of the engine tested – total of residues MS = 423,2653

As it results from Fig 4, the greatest influence on the HC concentration have: fuel temperature, followed by torque and the engine speed.

Torque in the first place and engine speed in the second one, are the most significant parameters that affect the NO_x concentration. Fuel temperature does not play an important role in the NO_x formation in the combustion process. The greatest influence on mean indicated pressure has torque and, in the definitely lower extends – the fuel temperature. The greatest influence on mean indicated pressure and indicated power has in order: torque, engine crankshaft speed and fuel temperature. Fig 5. illustrates the dependence of the measured and approximated values of HC concentration in a outlet manifold of the engine tested.

Engine torque has the most significant influence on CO concentration in a outlet manifold. At torque boost, the dose of fuel increases, air excess coefficient λ decreases and it results in the complete and incomplete combustion. Increase in torque T at constant air excess coefficient λ goes with the decrease of CO concentration. The decrease in torque T causes decrease in combustion temperature, which also involves the decrease in CO concentration.

Decrease in t_{pal} results in deterioration of the quality of fuel pulverization and injected fuel droplets diameters worsen the condition of fuel evaporation, which is caused also by the temperature decrease in the centre of fuel injection. Then, self-ignition delay increases, which causes interferences in the combustion course and as a result increases the amount of products of incomplete combustion, including the increase of CO in the engine exhaust gases.

The amount of toxic compounds in exhaust gases in the test engine increases along with engine load as a result of decrease in λ and increase in combustion temperature. When torque T (from $T = 25$ N·m to $T = 125$ N·m), at $n = 800$ [rev/min] increases, CO concentration increases as well – Fig 6.

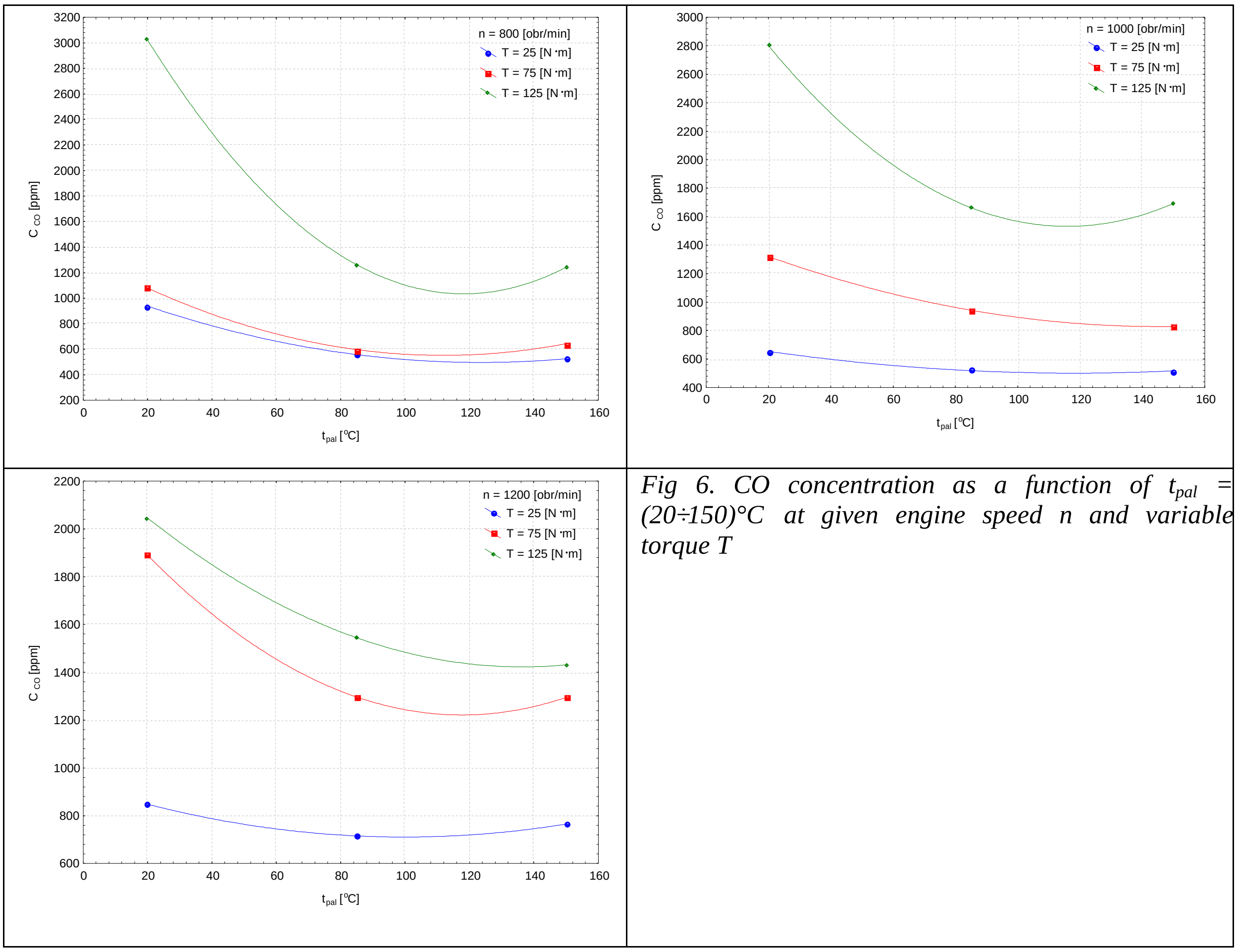

Fig 6. CO concentration as a function of t_{pal} *= (20÷150)°C at given engine speed n and variable torque T*

The greatest influence on the increase in NO_x concentration in four cycle engine has the torque (*T*). It results from the fact that two factors: temperature and amount of oxygen, playing a significant role in NO_x formation, affect one another. Along with the increase in torque *T*, *the value of* λ decreases, which results in temperature increase at the simultaneous decrease in oxygen concentration Along with the increase of toque *T* (from $T = 25$ to $T = 125$ [N·m]) at $n = 1000$ rev/min, the air excess coefficient λ decreases., which results in the increase in oxygen concentration in exhaust gases.

In general, an increase in temperature of injected fuel leads to decrease in NO_x concentration in exhaust gases, which is the most noticeable in the temperature range 50÷100°C. Thermal activation of fuel is the most efficient at low loads, because along with the increase in engine load, the effectiveness of this procedure radically changes and leads to a completely inverse situation, which is illustrated in Fig 7

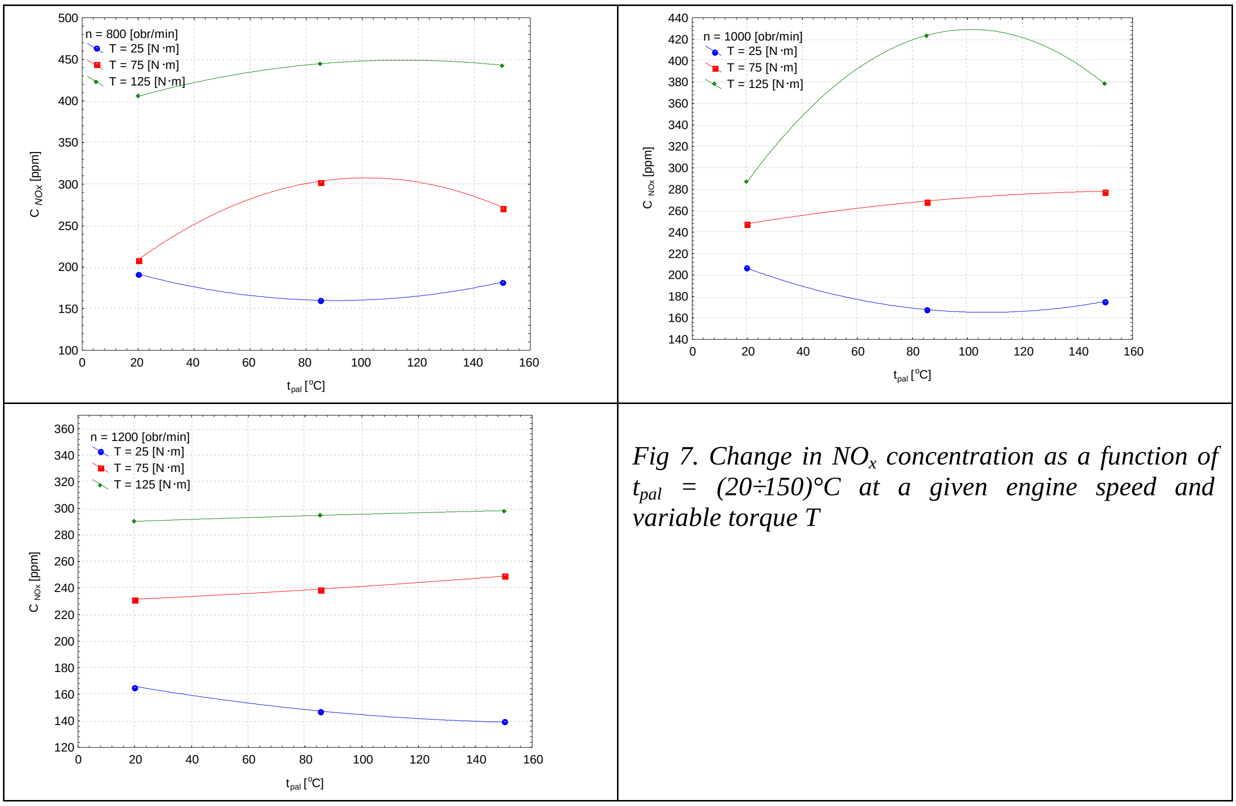

Fig 7. Change in NO_x concentration as a function of t_{pal} = (20÷150)°C at a given engine speed and variable torque T

As it was mentioned above, the principal influence on the increase in *HC* concentration in a outlet manifold has the temperature, what was verified in the statistical analysis. It is shown in Fig. 8.

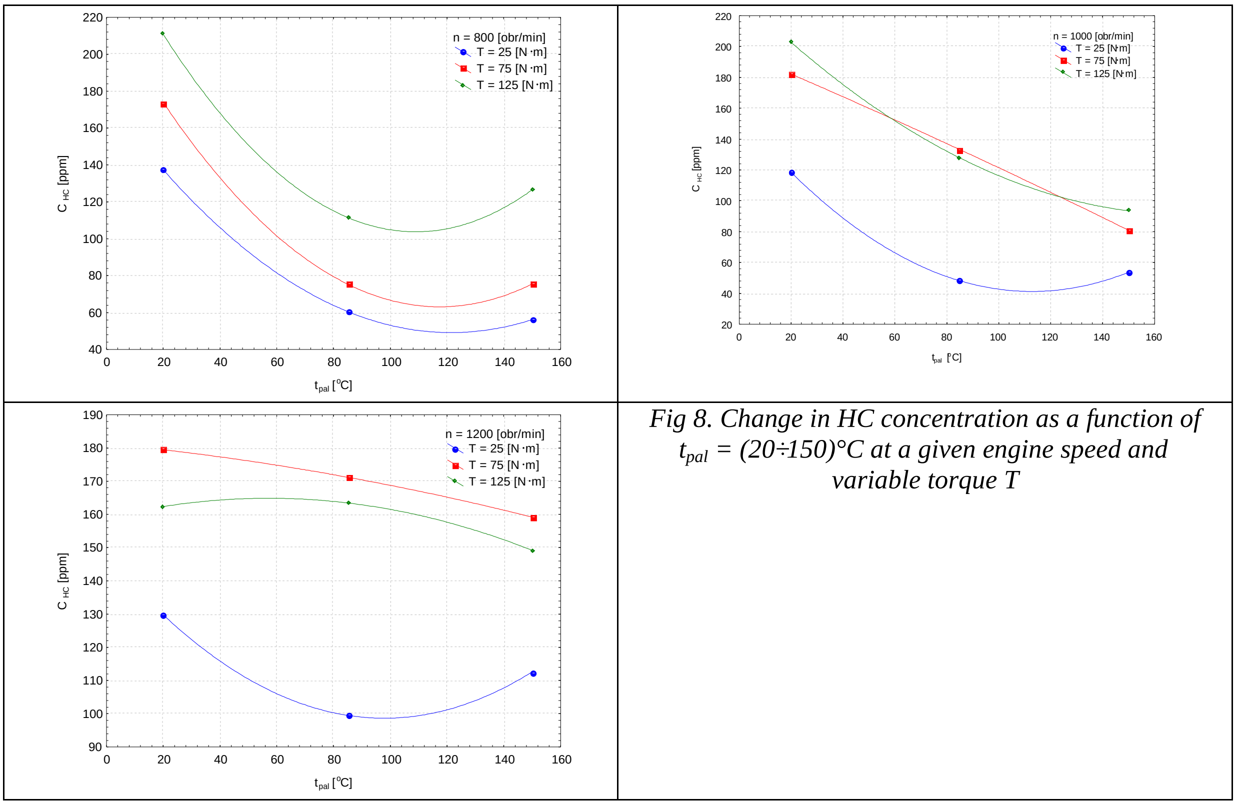

Fig 8. Change in HC concentration as a function of t_{pal} = (20÷150)°C at a given engine speed and variable torque T

It was possible to receive the decrease in uncombusted hydrocarbons along with the increase in t_{pal} (even to approx. 55% of the values received at t_{pal} = 20°C). However, it depends on engine work conditions: an increase in both its load and torque powers that beneficial effect.

The increase in *HC* concentration in exhaust gases, as a result of increase in torque T, at a given engine speed n, results from the decease in air excess coefficient λ. It is assumed, that in some areas of the combustion chamber there can appear local decrease in λ to value (λ<<1), which has the significant influence on increase in the number of uncombusted fuel particles. As a result, it leads to increase in *HC* concentration in exhaust gases. It is noticeable that *HC*, similarly to *CO*, mainly forms as a result of heterogeneous air-fuel mixture. This heterogeneity, in high extend depends on the structure of combustion chamber and its system of air filling and fuel feeding.

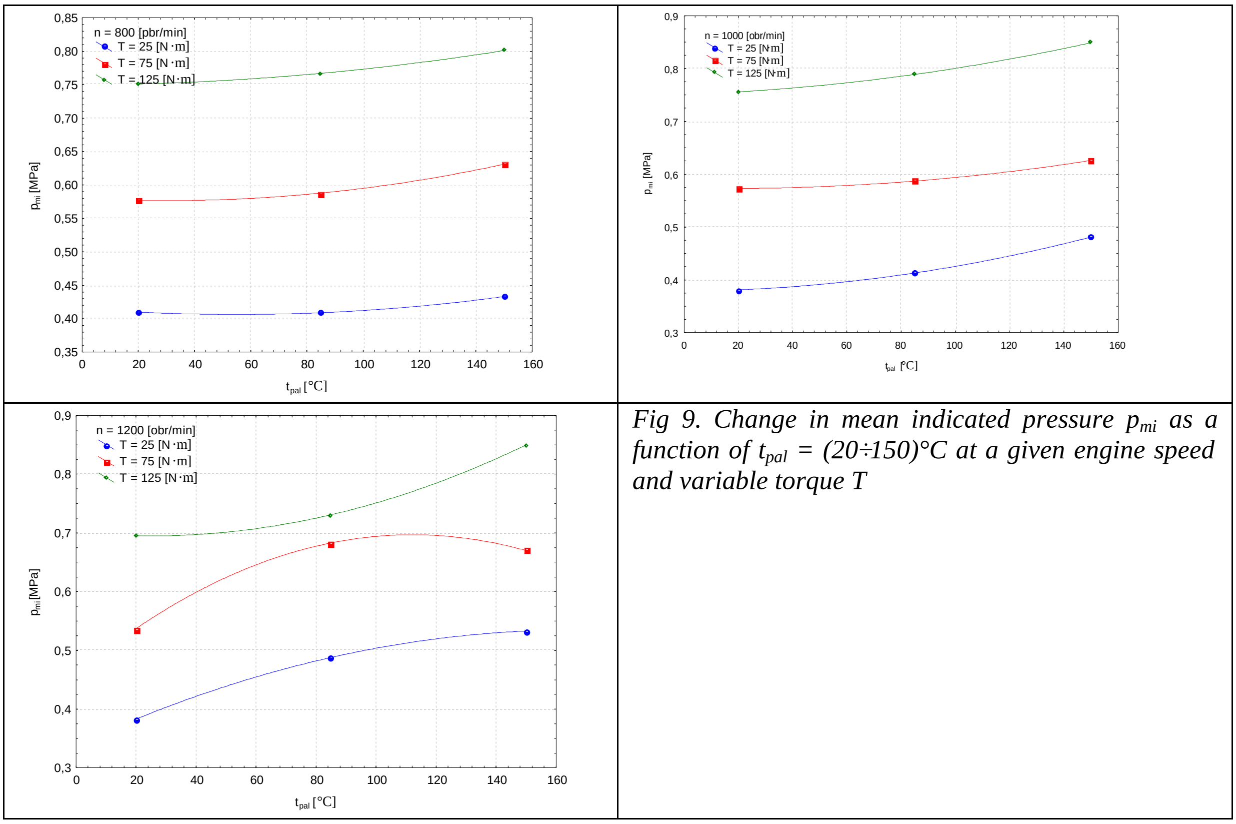

Fig 9. Change in mean indicated pressure p_{mi} as a function of t_{pal} = (20÷150)°C at a given engine speed and variable torque T

Torque has the main influence on the increase in mean indicated pressure in engine cylinder. Second in order is the fuel temperature t_{pal} (Fig 9).

Equation of the regression of *CO*, NO_x and *HC* concentration, mean indicated pressure p_{mi} and indicated power N_i in the range of t_{pal} = (20 ÷ 150)°C, n = (800 ÷ 1200) rev/min and T = (25 ÷ 125) N·m are the following:

$$\begin{aligned}[C_{CO}] = {} & +252.8545 - 19.8306t_{pal} + 0.0703t_{pal}^2 + 0.8471n - 0.0003n^2 + 15.0177T \\ & + 0.0658T^2 + 0.0086t_{pal}n - 0.0736t_{pal}T - 0.0068nT\end{aligned}$$

$$\begin{aligned}[C_{NOx}] = {} & -228.7217 + 0.9116t_{pal} - 0.0033t_{pal}^2 + 0.6561n - 0.0003n^2 + 3.5422T \\ & + 0.0045T^2 - 0.0006t_{pal}n + 0.0053t_{pal}T - 0.0027nT\end{aligned}$$

$$\begin{aligned}[C_{HC}] = {} & 479.2674 - 2.7329t_{pal} + 0.0056t_{pal}^2 - 0.7529n + 0.0004n^2 + 2.1907T - 0.0066T^2 \\ & + 0.0014t_{pal}n - 0.0011t_{pal}T - 0.0005nT\end{aligned}$$

$$[p_{mi}] = 0.3246 - 0.0014\mathrm{t_{pal}} + 0.0000\mathrm{t_{pal}}^2 - 0.0001n + 0.0000n^2 + 0.0050T - 0.0000T^2 + 0.0000t_{pal}n + 0.0000t_{pal}T - 0.0000nT$$

$$[N_i] = -6.3612 - 0.0278t_{pal} - 0.0000t_{pal}^2 + 0.0171n - 0.0000n^2 + 0.0844T - 0.0001T^2 + 0.0001t_{pal}n - 0.0001t_{pal}T + 0.0000T$$

Dependence of NO_x concentration on the values of input values (including fuel temperature) is presented in Fig 10, whereas the dependence of mean indicated pressure on these values is presented in Fig 11.

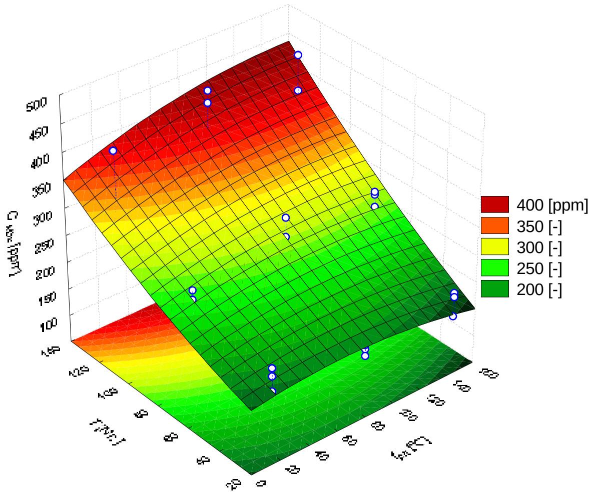

Fig 10. NO_x concentration as a function of t_{pal} and T

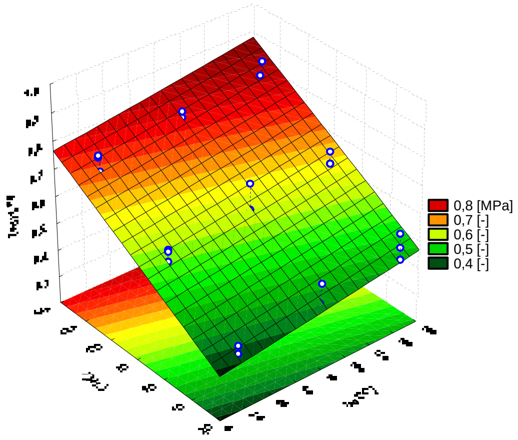

Fig 11. Mean indicated pressure p_{mi} as a function of t_{pal} and T

The highest increment of mean indicated pressure value (28%) for heated fuel is at n =1200 rev/min and T = 25 N·m. Low increments of this pressure are registered at low engine speed and high load. The increment is low and it reaches only (6%) in regard to the same load at unheated fuel.

3. Conclusions

The main aim of the use of thermal activation of fuel was to estimate energy and ecological effects of heating fuel in the feed system of vessels combustion engine. Considering the influence of temperature of injected fuel on analysed engine performance index, it is rational to search its optimal value.

Mentioned above factors must be considered up to the arbitrary decisions while making an attempt of finding the optimal values t_{pal},. Also engine work conditions must be taken under consideration while comparing the results for particular values t_{pal}.

On the basis of test results it can be stated that:

1) Along with the increase in engine load, there is a decrease in fuel temperatures, required for the most beneficial effects of heating the fuel.
2) Optimal fuel temperature in the range of (80÷120)^{o}C apparently decreases the power input necessary to its receiving in proportion to the input required at t_{pal} = 150^{o}C (they comprise at average (80÷90)% of the input at heating up to 150 ^{o}C). The range of temperature given above constitutes also the most beneficial range in proportion to the decrease in toxic compounds emission.

Feeding the engine by heated fuel brings on generally beneficial results. During proceeded tests there were obtained the following decreases in:

- HC concentration for about 44% (100 ppm)
- Carbon monoxide CO concentration for about 40% (1200 ppm)
- NO_x, concentration for about 22% (50 ppm), but only at low load, because at high load NO_x, concentration increases for about 20% (50 ppm).

Considering energy parameters of the engine fed by heated Diesel fuel in comparison with cool fuel, there was remarked the increment of:

- mean indicated pressure for about 14% (0.1 MPa)
- indicated power N_i for about 13% (3 kW).

Comparing research conducted on the test stand in LEUO with tests carried out by I. Pielecha from Poznan University of Technology it is possible to state that the obtained results do not differ much, although in the research of Poznan University of Technology the fuel was heated up to 220°C, while in the research of Naval Academy of Gdynia it was heated up to 150°C.

Literature

[1] Merkisz J.: *Ekologiczne problemy silników spalinowych, tom 1,2*, Wydawnictwo Politechniki Poznańskiej, Poznań 1999.

[2] Kowalewicz A.: *Podstawy procesów spalania*. Wydawnictwa Naukowe-Techniczne, Warszawa 2000.

[3] Baczewski K., Kołdoński T.: *Paliwo do silników o zapłonie samoczynnym*. WKiŁ, Warszawa 2004.

[4] Teodorczyk A.: *Teoria silników spalinowych.* Wydanie 1. Warszawa 2006.

[5] Piaseczny L.: *Zastosowanie teorii planowania doświadczeń w badaniach okrętowych silników spalinowych,* Zeszyty Naukowe Akademii Marynarki Wojennej, Rok XLIV nr 1 (152) 2003.

[6] Kafar I., Merkisz J., Piaseczny L.: *Model rozpylania paliwa w średnioobrotowym silniku okrętowym i jego badania symulacyjne*. Silniki Spalinowe, nr 3/2006 (126).

[7] Kowalczyk M.: *Diesel engine exhaust emmission control through pre-injection fuel thermal activation,* Archivum Combustionis. No. 1-4, Vol. 17 (1997).

[8] Pielecha I.: *Badania nad możliwością obniżenia emisji tlenków azotu silnika wysokoprężnego przez zastosowanie zewnętrznej aktywacji termicznej wtryskiwanego paliwa.* Praca doktorska. Politechnika Poznańska, 2000.