SIMULATION OF AN INDICATOR DIAGRAM OF A DIESEL ENGINE

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INTRODUCTION

Cooperation conditions of a diesel engine with a specific automotive vehicle determine the maximum power it should develop at any rotational speed of the crankshaft. Rationalization and optimization of an engine's working cycle at a required power, i.e. its energy, economical and ecological factors are reduced to the definition of conditions under which it reaches the maximum values of effective efficiency η_e, at the permissible mechanical and thermal loads, permissible emission of toxic components in exhaust gas and noise. In the process of an analysis and selection of the fuel and air supply systems of an engine, one has to distinguish quantitative and qualitative parameters of fuel injection and spraying characteristics, and such parameters of characteristics of the working medium transfer within the cylinder, that show an essential influence on the above listed engine factors. A clear indication of concrete parameters connected with an engine's construction and adjustment is possible only in case of sufficient knowledge of the whole chain of processes responsible for heat release during the combustion process. In the authors' view, this chain includes: fuel spraying process – flammable mixture forming – the combustion definition of an engine's working factors (indices).

Despite considerable achievements in the research on different links of the chain, up to now this problem has not been studied in a sufficient and exhaustive manner. Therefore, when analyzing parameters and characteristics of fuel injection and spraying, and characteristics of the working medium transfer processes within the cylinder, one has to take into consideration trends, methods and research means of the said chain of processes. Taking into consideration the actual state of knowledge concerning the processes of that chain, it is necessary to determine the parameters and characteristics of supplying fuel and oxidizer to the cylinder, having decisive influence on the processes taking place in turn or in parallel.

In the present research work a methodology was elaborated concerning the determination by simulation of an indicator diagram of a diesel engine, on the basis of a given characteristics of speed, relative amount of heat released during the combustion process. The methodology in question takes into consideration variations of quality and number of working medium moles during the combustion process, variations of its temperature, and heat transfer between working medium and walls delimiting the combustion space.

PARAMETERS AND FACTORS INFLUENCING THE WORKING INDICES OF AN ENGINE

Besides parameters defining quantitative and qualitative filling of the cylinder, a very important and direct influence on the working indices of an engine is shown by the volume of fuel charge injected per one working cycle of the engine and by the injection time. The volume of fuel charge supplied to the cylinder has a decisive influence on energy and the specific working indices of the engine, and on its influence on the natural environment.

The value of mean effective pressure p_e, power per 1 dm^3 of the engine displacement N_l and effective engine power N_e are determined from the equations:

$$p_e = \frac{m_c \cdot W_u \cdot \eta_i \cdot \eta_m}{V_s} \tag{1}$$

$$N_l = \frac{p_e \cdot n}{30 \cdot \tau} \tag{2}$$

$$N_e = N_l \cdot V_s \cdot i \tag{3}$$

where:

m_c – fuel charge per one working cycle,
W_u – fuel calorific value,
V_s – cylinder displacemen,
n – rotational crankshaft speed,
i – number of cylinders,
τ – number of piston strokes per one working cycle of the engine,
η_i – indicated efficiency,
η_m – mechanical efficiency.

For a diesel engine having given geometrical dimensions, parameters of air flowing into the cylinder and fuel charge injected per one working cycle determine the excess air number λ:

$$\lambda = \frac{V_s \cdot \rho_s \cdot \eta_v}{m_c \cdot l_o} \tag{4}$$

where:

ρ_s – air density in an intake system,
η_v – cylinder filling ratio,
l_o – theoretical amount of air required for total and complete combustion of 1 kg fuel.

METHODOLOGY AND ALGORITHM OF NUMERICAL SIMULATION OF INDICATOR DIAGRAM OF A DIESEL ENGINE

Methodology and computing algorithm, making possible indicator diagram plotting for a given characteristics of heat release speed during combustion process, were elaborated on the basis of the first law of thermodynamics and equation of state of working medium, taking into consideration the dependence of specific heat on temperature and excess air number λ, and fuel reaction ratio x [4, 5]. It was assumed that dissociation level of combustion products within the cylinder of the engines is small, and heat losses caused by the said effect may be omitted. For this reason the system of equations describing the heat release process within the cylinder is as follows:

$$\left.\begin{aligned} dQ_x &= dU + pdV + dQ_{sc} \\ pV &= MRT \end{aligned}\right\} \tag{5}$$

The amount of heat released from combustion of fuel charge is calculated from the equation:

$$dQ_x = \xi \cdot m_c \cdot W_u \cdot dx \tag{6}$$

Variation of isochoric specific heat value is calculated from the equation:

$$c_v = \frac{R}{k-1} \tag{7}$$

where:

$$k = 1{,}259 + \frac{76{,}7}{T} - \left(0{,}005 - \frac{0{,}0372}{\lambda}\right) \cdot x \tag{8}$$

Heat exchanged with the walls of combustion chamber space is calculated according to Newton's formula:

$$dQ_{sc} = \alpha_p \cdot F \cdot \frac{d\alpha}{6 \cdot n} \tag{9}$$

The value of the overall heat transfer coefficient α_p was calculated according to the formulae of Woshni, Hardenberg and others, given in [3]. Solving the system of equations (5) taking into consideration equations (6-9), and replacing differentials with finite differences, we obtain:

$$p_i = \frac{1}{A} \cdot \left[\begin{aligned} & 2 \cdot \xi \cdot m_c \cdot W_u \cdot \Delta x + p_{i-1} \cdot \left(\frac{k+1}{k-1} \cdot V_{i-1} - V_i \right) \\ & + \alpha_p \cdot F \cdot \left(2T_{sc} - \frac{p_{i-1} \cdot (V_i - V_{i-1})}{2MR} \right) \end{aligned} \right] \cdot \frac{\Delta\alpha}{6n} \tag{10}$$

where:

$$A = \frac{k+1}{k-1} \cdot V_i - V_{i-1} + \alpha_p \cdot F \cdot \frac{V_i + V_{i+1}}{2MR} \cdot \frac{\Delta\alpha}{6 \cdot n} \tag{11}$$

$$F = \pi \cdot D \cdot \left(\frac{D}{2} + S_o + S_i \right) \tag{12}$$

In the above listed equations the following symbols were used: D – cylinder diameter; S_i – instantaneous value of piston stroke; S_o – distance between piston and cylinder head plane at TDC; ζ – heat release ratio.

Using the above presented equations, and computing the well-known formulae applied to the theory of internal combustion engines, an algorithm was elaborated followed by a computer program, making it possible to plot an indicator diagram and determine the indicated parameters and indices of an engine.

SUBJECT AND SCOPE OF NUMERICAL RESEARCH

Due to the availability of technical data, and a large library of experimentally elaborated indicator diagrams of a 359 engine running under different conditions and adjustments, this engine was chosen as the test object. The engine in question is used in vehicles of STAR family. Simulation plotting of indicator diagrams for this engine was carried out for three assumed velocity characteristics of a relative amount of the released heat. Calculations were performed with the assumption that combustion takes place in a complete and absolute manner. This allows to assume that the area between the velocity characteristics of a relative amount of released heat and axis of abscissa is equal to 1. Calculations were performed for the rotational speed $n = 1900$ min^{-1} and different values of fuel injected per one working cycle $m_e \in \{21, 31, 52\} \cdot 10^{-6}$, kg/cycle. Heat release times, determined by crankshaft rotation angles, belonged to the set $\alpha_{spl} \in \{15, 26, 35\}^o\,OWK$. Velocity characteristics of a relative amount of released heat $\dot{x}$ were assumed in forms of rectangle. That characteristic is shown in Figure 1.

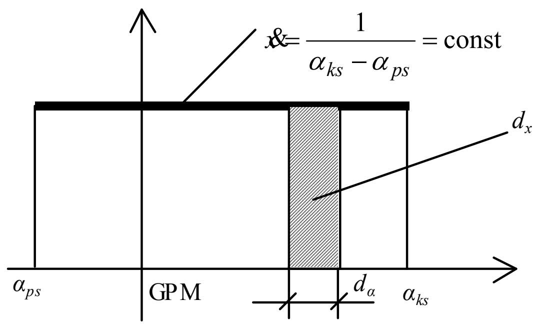

Fig. 1. Rectangular velocity characteristics of a relative amount of released heat

The excess air number λ affects the indicated efficiency of an engine not only by modifying combustible mixture quality and its combustion, but also other quantities depending on it. Even under ideal conditions, that may be understood as immediate mixing and combustion of supplied fuel charge, the decrease of λ causes the decrease of heat utilization ratio as a result of increase of temperature and thermal capacity of working medium within the cylinder. Results of calculations, performed assuming ideal conditions for forming and combustion of combustible mixture in 359 engine with D/S =110/120 (combustion chamber in piston) and at n = 2000 min^{-1}, as well as assuming constant heat release velocity during the combustion process in Fig. 1, are shown in Table 1. Heat transfer was calculated according to Woschni's formula.

Table 1. Influence of injected fuel charge value on engine working cycle, its parameters and energy indices

Parameter	Fuel charge per engine working cycle $m_c = 31 \cdot 10^{-6}$ (kg/cycle)		
	52	31	21
Self-ignition angle α_{sz} (°OWK)	4	2	0
Heat release duration angle α_{spl} (°OWK)	26	20	16
Maximum cycle pressure p_z (MPa)	7.92	6.79	5.82
Maximum cycle temperature T_z (K)	2107	1687	1434
Overall heat transfer coefficient α_p (W/(m^2·K)$^{-1}$)	538.5	456	404
Amount of heat exchanged with cylinder walls Q_{sc} (%)	16.62	15.31	16.67
Theoretical efficiency of calculated engine working cycle η_{to}	0.505	0.53	0.539
Mean pressure of calculated engine working cycle p_{to} (MPa)	0.981	0.618	0.418

Results shown in Table 1 lead to the conclusion that 2.5-times increase of fuel charge (and respective decrease of λ number) caused the decrease of theoretical efficiency by about 6.3%. Mean theoretical cycle pressure p_{to} increased to a lesser extent than fuel charge, since about 2.30-times only. With the increase of fuel charge, maximum cycle parameters i.e. p_z and T_z also increased. Relative heat losses to walls Q_{sc} reached their minimum value at $m_c = 31 \cdot 10^{-6}$ kg/cycle. An increase of these losses took place both with an increase and with a decrease of fuel charge per cycle. A change of fuel charge per cycle affected also other parameters such as fuel injection duration, reach of injected fuel streams, fuel distribution over combustion chamber volume and wall zones, atomizing and others. The said parameters also affected the values of the above listed working parameters and indices of the engine. Table 2 shows an influence of combustion processes period on the fundamental parameters of the working cycle of 359 engine.

Table 2. Influence of heat release duration on working parameters and indices of 359 engine

Parameters and indices	Heat release duration α_{spl} (°OWK)		
	15	26	35
Self-ignition angle α_{sz} (°OWK)	-0.5	4	7
Maximum cycle pressure p_z (MPa)	8.9	7.92	7.62
Maximum cycle temperature T_z (K)	2243	2107	1980
Overall heat transfer coefficient α_p (W/(m^2·K)$^{-1}$)	540	538	534
Amount of heat exchanged with cylinder walls Q_{sc} (%)	17.6	16.5	16.0
Theoretical efficiency of calculated engine working cycle η_{to}	0.509	0.505	0.489
Mean pressure of calculated engine working cycle p_{to} (MPa)	0.986	0.978	0.966

An increase of heat release duration caused a decrease of cycle efficiency. At the same time both the maximum temperature and the maximum cycle pressure decreased.

The elaborated methodology of an indicator diagram numerical simulation and calculation of parameters of the indices of an engine makes it possible to analyse an influence of different forms of heat release velocity characteristics on the set of values characterizing an engine's operation, and a change depending on these characteristics. This information will make it possible to more precisely define the improvement trends of basic engine blocks and its optimum adjustment in connection with the selected function. This problem is essential, especially in case of research work connected with evaluation and rationalization of modern internal combustion engines equipped with electronic control systems.

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SUMMARY

The present paper deals with simulation methodology of an indicator diagram of an engine on the basis of an assumed velocity characteristics of a relative amount of heat released during the combustion process, taking into consideration variations of the amount and characteristics of the working medium.