THE METHOD OF SIMULTANEOUS PARAMETRIC ANALYSIS OF THE IN-CYLINDER PROCESSES AND THERMAL LOAD ON DIESEL PISTON UNITS

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Abstract

The paper describes the basic methodological principles and the results of development and practical application of simultaneous complex parametric analysis of the in-cylinder processes and thermal load on cylinder piston unit in diesel engines. The application of the suggested method to research and conceptualize engine design allows us to choose an optimal combination of the cylinder-piston unit parameters and diesel engine control. As a result, an admissible level of thermal stress in the most heavily loaded parts of cylinder-piston unit and low fuel consumption of diesel engines are achieved. A limited number of factors determining perfect in-cylinder processes make this method easy to visualise as well as providing it with a clear physical meaning of graphically presented results, not restricting the analysis to the design parameters of engine units. The method was practically used for upgrading high-speed diesel engines of the trademarks CHN 16.5/18.5, CHN 15/18, and CHN 15/15, to increase their power based on the average indicated pressure, and to reduce their fuel consumption and harmful environmental effects. In particular, a method implemented in diesel engines CHN 15/15 of the basic design with their power increased by 60-70%, the power of diesel CHN 16.5/18.5 was increased by 70–100%.

Keywords: *diesel engine, thermal stress, in-cylinder processes, low fuel consumption, mathematical modelling*

1. Introduction

The unification of design and manufacture of modern standard diesel engines is based on modular approach which can provide better quality, operating characteristics and lower maintenance costs of diesel engines [11].

An optimal choice of basic parameters helps to create favourable conditions for developing diesel engines of basic design with better operating characteristics, whereas errors made at the initial stage of design increase the cost of research and elimination of engine defects [4]. The application of the described method is associated with the proper choice of basic methodological principles determining the major parameters of the in-cylinder processes which could ensure low fuel consumption, admissible thermal and mechanical stresses in diesel engine units and low emission of toxic gases. The solution of these problems in the present investigation allowed the authors to develop a method based on simultaneous parametric analysis of the in-cylinder processes and thermal stress in the cylinder piston unit (CPU) of diesel engine. The suggested method is based on the dependence of the indicator efficiency and boundary conditions of the third type heat exchange in the cylinder on diesel engine parameters, such as excess-air coefficient, compression and pressure increase in combustion, pressure and temperature of supercharging air.

The developed approach was successfully applied to the experimental research in modifying high-speed standard diesel engines CHN 16.5/18.5 (D = 165 mm, S = 185 mm). The engines' loading ranged from 70 to 100% with respect to the average effective pressure up to P_{me} = 1.8-2.0 MPa, when the module approach to aggregating various engine models [8] was used. The experience gained was extended to diesel engines of the models CHN 15/18 (D = 150 mm, S = 180 mm) and CHN 15/15 (D = 150 mm, S = 150 mm).

2. Basic methodical principles of simultaneous parametric analysis

To assess the control techniques of the in-cylinder processes of diesel engines, taking into account fuel consumption, methods based on general graphical relationships describing their major parameters are widely used in practice. A relatively small number of variables indicating thermodynamical characteristics of the processes are analysed. This is suitable and sufficient for practical purposes as far as structurally similar diesel engines with various levels of loading, basic systems and operating characteristics are considered.

Investigations to improve the combustion piston engines are leading to improve the working process performance by increase of its parameters, especially the average temperature of the thermodynamic cycle. This increases the demands on the elements surrounding the engine combustion chamber, mostly pistons, which already belong to the very stressed structures. Another requirement of environmental standards posed on internal combustion engines used to power automobiles is the low level of noise emitted to the environment. [11]

Thermal shocks are reasons for high temperature gradients occurring in materials of engine components, what in turn makes for high total stresses, even at lack of mechanical loads that accelerate damage of the engine components. With reference to heterogeneous elements like materials with covers, temperature gradients will be considerably greater and will represent what is due to different material properties. The resistance to the piston thermal shocks made up from composite materials is especially essential for heavy-duty Diesel engines. [4].

However, at the research and conceptual design stages of developing diesel engines of basic design, the problems of determining thermal stress of the most heavily loaded parts of the CPU arise. Usually, the application of experimental and advanced calculation methods based on multizone models, as well as rapidly developing integrated systems of computer-aided design CAD/CAM/CAE/EPD (Unigraphics, Euclid Quantum, etc.), causes difficulties because great amounts of various combinations of parameters should be evaluated. [1, 2, 3, 4, 5, 8, 11, 13, 14].

In this work, the investigation of the essential parameters of the in-cylinder processes is made with the use of the software package 'Impulse'. This package allows closed modelling of operating characteristics of turbo-piston diesel engines to be performed. To calculate the coefficient of the average convective heat transfer from the working medium along the surface of the piston, formula α_G developed by CNIDI (Central Diesel Research Institute, St. Petersburg, Russia) [9].

The use of α_G formulas for practical development of diesel engines is still effective. This is confirmed by the developers of currently used multizone methods of calculating heat exchange rate [5]. In particular, a corrected α_G formula suggested by Woschni is used for investigating both diesel and gas engines [12]. Like G. Woschni's α_G formula, it is based on the use of the criterion equation of the form $Nu = APr^nRe^m$. The constants A, n, and m are determined based on the data obtained in testing a wide range of high- and medium-speed diesel engines.

The curve of distribution $\alpha_{Gi} = f(R)$ along the radius of a vibrating (oscillating) system was obtained based on the available experimental data on similar diesel engines and by solving the inverse heat transfer problem.

2.1. Generalised relationships describing in-cylinder processes

A widely used method of searching for an optimal efficiency value η_i of the in-cylinder processes relying on its general relation with the essential parameters of these processes (excess-air coefficient (α), increase in cylinder pressure, i.e., the ratio of maximum gas pressure in the cylinder to the pressure at the end compression ($\delta = P_{\max}/P_c$), pressure and temperature of the air charge at the beginning of compression (P_a, T_a) and compression ratio (ε) [10] was taken as a basis. The validity of the considered approach may be increased by the analysis of the experimental data obtained for the prototype diesel engines.

According [6], the interrelationship between the cycle parameters is presented as graphical relationships between a complex indicator of loading level $\Pi = P_{\max}/(P_{mi})(350/T_a)$ and η_i as the function of $P_{\max}/P_a$, when α is invariant (here, $P_{\max}$ and P_{mi} are the maximum combustion pressure in the cylinder of diesel engine and the average indicated pressure, respectively. The relation $P_{\max}/P_a$ is the product of two basic parameters of in-cylinder processes $\varepsilon^{n1}\delta$). As a result, a functional relationship Π, $\eta_i = f(P_{\max}/P_a, \alpha)$ allows us to perform the analysis of the in-cylinder processes based on a number of essential parameters, depending on the level of loading, the admissible mechanical loads on the units and the temperature of the supercharging air (P_{mi}, $P_{\max}$ and T_a, respectively). Thus, the optimum η_i value depends on the proper choice of ε, when α, $P_{\max}$, δ and P_a (P_k - the pressure of supercharging air for supercharged engine, P_o - the pressure of supercharging air for non-supercharged engine) are specified.

Therefore, to perform a simultaneous parametric analysis, the interrelationship between the indicators of thermal loads on the CPU parts in the function of the parameters, also determining the economical operation of diesel engine, should be established.

2.2. Establishing the interrelationship between control parameters and thermal load on the piston

Interrelationship between the average cyclic coefficient of the convective heat transfer from the working medium to the walls of the CPU parts as well as the working medium temperature $\alpha_{G.m}^{\mathrm{DET}}, T_{G.m}^{\mathrm{DET}}$ $(\alpha_{G.m.H}^{\mathrm{DET}}, T_{G.m.H}^{\mathrm{DET}})$ and the parameters of the in-cylinder processes has been established and investigated based on the model developed in [6]. This is a mathematical model of a high-speed diesel engine cycle allowing us to calculate current values of the parameters of the working medium (i.e., pressure and temperature) and convective heat transfer characteristic associated with the cycle time T_G, P_G, $X = f(\alpha, \varepsilon, \delta, P_a, T_a)$, where X is the heat release rate. The coefficient of convective heat transfer from the working medium in the piston head can be described by the following equation in accordance with the relationship from α_G – formula:

$$\alpha_G = \left(2.75 + 58.6\frac{D}{C_m}\right)\frac{\lambda_G}{\mu_G^{0.5}}\left(\frac{C_m}{D}\right)^{0.5}\left(\frac{P_G}{R_G T_G}\right)^{0.5}, \mathrm{W/(m^2 \cdot K)}, \tag{1}$$

where:

λ_G - the heat transfer coefficient of gas, W/(m·K),

μ_G - the gas viscosity, kg/(m·sec),

P_G and T_G - gas pressure and temperature, respectively N/m^2 and K,

C_m - the mean piston speed, m/sec,

D - the diameter of the cylinder, m,

R_G - is the gas constant, J/(kg·K).

Then, the local convective heat transfer coefficient with respect to the cycle time will be as follows:

$$\alpha_G = N \frac{\lambda_G}{\mu_G^{0.5}} \left(\frac{P_G}{R_G T_G} \right)^{0.5} . \tag{2}$$

For diesel engines of similar design and for constant speed mode n and $C_m = const$, a cofactor $\left(2.75 + 58.6 \frac{D}{C_m}\right)\left(\frac{C_m}{D}\right)^{0.5}$. is substituted for constant (N).

A transfer to simultaneous parametric analysis is reflected by a system of equations:

$$\begin{cases} T_G, P_G, X = f(\alpha, \varepsilon, \delta, P_a, T_a), \\ \lambda_G, \mu_G = f(\alpha, X, T_G), \\ \alpha_G = N \dfrac{\lambda_G}{\mu_G^{0.5}} \left(\dfrac{P_G}{R_G T_G} \right)^{0.5} . \end{cases} \tag{3}$$

The solution of these equations allows us to express the condition of parametric similarity of heat transfer from the working medium in the piston head by the relationship α_G, $T_G = f(\varepsilon, \alpha, \delta, P_a, T_a)$ (at the beginning of compression, the temperature and pressure in the cylinder are assumed to be equal to the temperature and pressure of supercharging air, and this does not cause any significant calculation error: $P_k \approx P_a$, $T_k \approx T_a$).

To determine functional relationship α_G, $T_G = f(\varepsilon, \alpha, \delta, P_a, T_a)$. A transfer to the average cycle values $\alpha_{G.m}$, $T_{G.m}$ $(\alpha_{G.m.H}^{\mathrm{DET}}, T_{G.m.H}^{\mathrm{DET}})$ is based on the statistical analysis of the data obtained in calculations.

It has been determined that the significant criteria (factors) rated based on their influence on $\alpha_{G.m}$, $T_{G.m}$ are as follows: α, ε, δ, P_a for $\alpha_{G.m}$ $(\alpha_{G.m.H}^{\mathrm{DET}})$ and α, T_a, δ, ε for $T_{G.m}$ $(T_{G.m.H}^{DET})$. For practical purposes, the relationships $\alpha_{G.m}$ $(\alpha_{G.m.H}^{\mathrm{DET}})$ and $T_{G.m}$ $(T_{G.m.H}^{\mathrm{DET}})$ are presented in the function of the interrelated diesel engine parameters $P_{\max}/P_a$, α, ε, δ, T_a with the same methodical approach applied to the choice of the most rational combination as that used in searching for optimal fuel consumption index η_i. The influence of the parameters of supercharging air entering the cylinder is shown by the introduction of cofactors $P_a^{-0.5}$ and $(T_a/350)^{0.5}$. In the final expression $\alpha_{G.m.H}^{\mathrm{DET}} / P_a^{0.5} = f(P_{\max}/P_a, \alpha)$ and $T_{G.m.H}^{\mathrm{DET}}$ $(T_a/350)^{0.5} = f(P_{\max}/P_a, \alpha, \varepsilon)$ [6].

In this way, the conditions are met, allowing us to perform simultaneous parametric analysis of the major characteristics of in-cylinder processes and thermal stress in the piston unit in the function of the values $P_{\max}/P_a$, α and ε or ε, α, δ, P_a and T_a, taking into account $P_{\max}/P_a = \varepsilon^n \delta$.

3. Simultaneous parametric analysis

Simultaneous parametric analysis of the in-cylinder processes based on fuel consumption and thermal load on piston means simultaneous investigation of all loading modes of diesel engines based on the average indicated pressure P_{mi}.

Finally, the analysis included the procedures performed in the following order:

1. The values of a complex parameter of diesel engine loading $\Pi = P_{\max}/(P_{mi})(350/T_a)$ are calculated for the considered level P_{mi} based on the values $P_{\max}$ and T_a set a priori (Fig. 1).
2. The domain of possible combinations of the parameters of in-cylinder processes is obtained as a result of the intersection of four rays of the fixed value $\alpha = 1.75$; 2.0; 2.25; 2.5 units with two

parallel lines $\Pi = \text{const.}$ (accounted for by a tolerance for diesel engine manufacture and adjustment).

3. When projecting the points on the axis of abscissas, the value of $P_{\max}/P_a$, which is used as a basis for determining P_a, when $P_{\max}$ is known, is found for each point.
4. To determine the value of ε, the known equality $P_{\max}/P_a = \delta\varepsilon^{n1}$ is used.
5. When the combinations of α, δ, ε, P_a, T_a are found by using the methods [6], $\alpha^{\mathrm{DET}}_{G.m.H}$ and $T^{\mathrm{DET}}_{G.m.H}$ are determined.
6. The obtained combinations of $\alpha^{\mathrm{DET}}_{G.m.H}$ and $T^{\mathrm{DET}}_{G.m.H}$ are marked on the nomogram plane as $\alpha^{\mathrm{DET}}_{G.m.H} - T^{\mathrm{DET}}_{G.m.H}$. Thus, each of the considered levels of loading based on P_{mi} is related to a particular local area (Fig. 2) restricted to eight combinations of $\alpha^{\mathrm{DET}}_{G.m.H}$ and $T^{\mathrm{DET}}_{G.m.H}$.

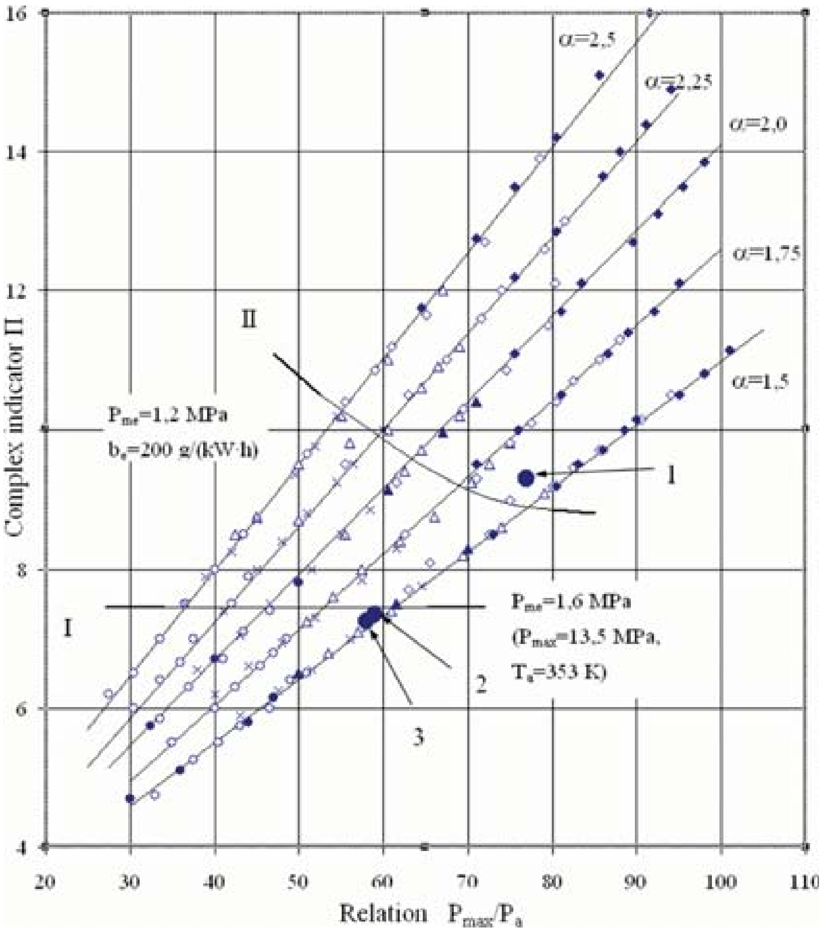

Fig. 1. The dependence of parameter $\Pi = P_{max}/P_{mi}$ $(350/T_a)$ in the function P_{max}/P_a and α for diesel engines CHN16.5/18.5 (n=1500 min-1, design of stage I): o,X,△,◇,◆- *ε=11,13,15,17,19 (P_{me}=1,4 MPa; T_a=353 K);* ■ *- P_{me}=1.8 MPa; T_a=333 K; for diesel engines 16.5/18.5: 1 - P_{me}=1.00 MPa; α=1.60; ε=17.8; 2 - P_{me}=1.55 MPa; α=1.45; ε=15.1; 3 - P_{me}=1.40 MPa; α=1.50; ε=15.1*

All considered combinations of α, P_a, δ, ε are invariant with respect to fuel consumption because in the sectors of the nomogram $\alpha^{\mathrm{DET}}_{G.m.H} - T^{\mathrm{DET}}_{G.m.H}$ they realise a condition of $b_i = const$ for the fixed P_{mi}, whereas for P_{mi} = 1.2–1.6 MPa they meet the condition of $b_e \approx const$. To make a rational choice of combinations based on thermal stress, its values admissible for safe operation of piston (maximum surface temperature and the temperature T_{DET} of particular zones and stress σ_{DET}) are marked in the nomogram by isolines of constant quantities. These values may be taken from the previous experiments and calculations. The use of several criteria in the analysis allows us to determine the limiting values, focussing greater attention on them in optimising the parameters of in-cylinder processes. As shown in Fig. 2, operational safety of a non-cooled piston depends on the temperature in the area of the first compression ring. Taking into account service conditions, the highest temperature t_{p1} = 220°C is adopted when oil additives are used.

Fig. 3 presents a nomogram illustrating the temperature and thermal stresses of a non-cooled welded piston (a) and exhaust valve (b) of a high-speed, high-powered diesel engine CHN15/18, with a Power-Driven Centrifugal Supercharger (PDCS), calculated by the finite element method (FEM).

It should be noted that the developed approach is not restricted to the analysis of quasistationary piston loading. Pistons may be assessed in terms of their fatigue strength, taking into account overall stresses developing under the action of a stationary temperature field and variable loads owing to the action of P_{max}. In this case, the available testing data on the fatigue of pistons in the form of Goodman–Serensen diagram may be used (as is common in diesel engine manufacture).

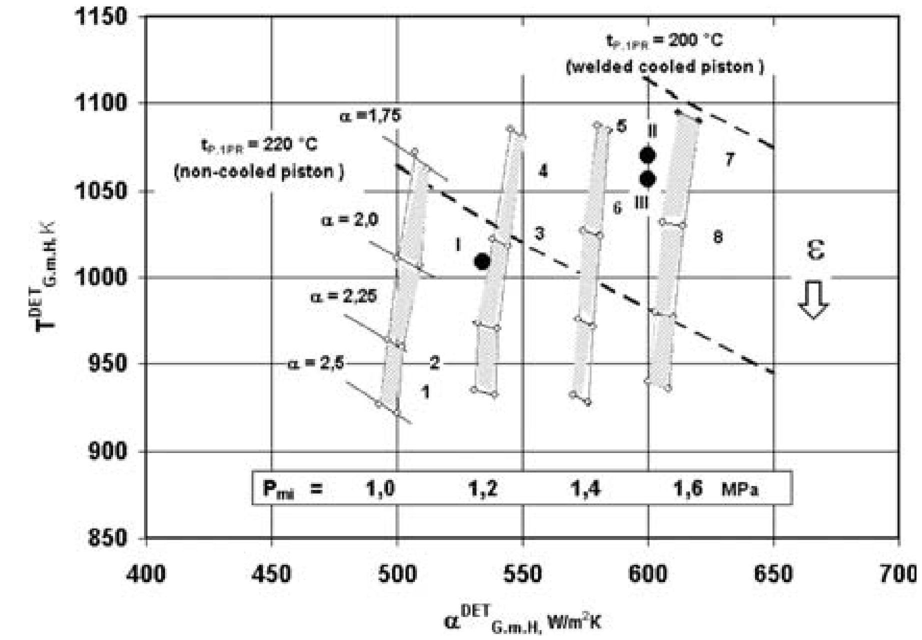

Fig. 2. A fragment of a simultaneous parametric analysis of in-cylinder processes and thermal load on CPU parts in loading diesel engines of basic design CHN 15/15 based on P_{mi} (with increasing P_{mi} and using of SAC at the temperature t_w= 100 °C; ● - a standard buildup: I - ε = 15.3; P_{mi} = 0.96 MPa, II - ε = 15.3; P_{mi} = 1.17 MPa, III - ε = 14; P_{mi} = 1.17 MPa)

The analysis of the arrangement of isolines T_{DET}, $\sigma_{\mathrm{DET}} = const$ and the planes of the considered engine loading levels with respect to each other, based on P_{mi}, allows us to perform variational evaluation of the in-cylinder processes and to determine the influence of its parameters on thermal stress. It also shows the benefits of using more advanced piston models (in particular, cooled pistons).

In Fig. 2, the application of the suggested method of simultaneous parametric analysis for a perspective build-up of diesel engines CHN 15/15 with the increased injection pressure P_{mi} and SAC-based cooling systems is illustrated. On the nomogram plane, shaded circles show thermal piston load for in-cylinder processes, when a cooling system without SAC is used. It is evident that, for diesel engines of the basic design loaded at 1.0 MPa, oil-cooled rather than non-cooled pistons should be used.

4. The use of a complex parametric analysis in increasing the power of diesel engines D20

In this section, the major results obtained in applying a method of simultaneous parametric analysis to the development of oil-cooled pistons for the high-powered diesel engines D20 are provided.

For the numerical study of temperature patterns of pistons, modern software packages - 'Solid Works' and 'Cosmos Works' created for designing 3D units and parts and mathematical modelling of temperature patterns, stresses and strains of units were used. The construction of a 3D finite element piston model allowed for a point study of its temperature patterns and stresses.

It has been found that a limiting criterion of the thermal stress state of a non-cooled piston is the temperature of the area of the first compression ring $t_{P.1PR}$.

Increasing the pressure of oil injection P_{mi} and using air cooler in the supercharging system (SAC) considerably extends the range of loading: theoretically, it may reach the upper limit of the above range of P_{mi} = 1.6 MPa, while piston build-up remains the same due to simultaneous increase of excess-air coefficient α and P_{mi},.

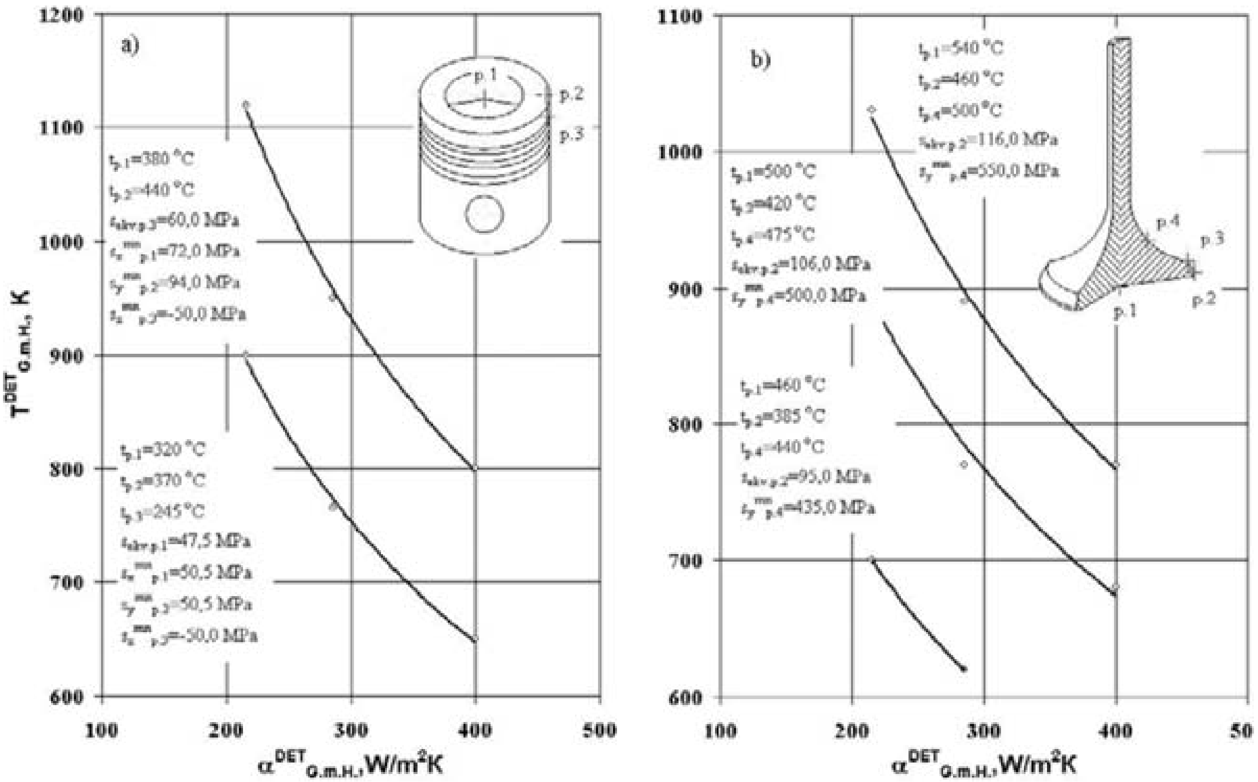

Fig. 3. Isolines of constant temperature and thermal stresses in typical zones for non-cooled piston (a) and exhaust valve (b) of the augmented diesel engine CHN15/18 with PDCS

To assess feasibility of using the specified values of α, bench mark data on the in-cylinder processes' parameters in the modes of possible power increase are presented in the area on the nomogram in Fig. 4 (unshaded circles for modes 1-8). In Table, the respective combinations of ε, α, P_k (π_κ) and T_k are given. For basic power increase it is not difficult to achieve the required α = 1.75 units. For the optimal compression ratio ε = 17 units, associated with low fuel consumption, the values of α = 2.25 units and $\pi_\kappa \approx 2.25$ units are obtained. The realisation of α = 2.0 units for P_{mi} = 1.2 MPa is associated with the decrease in ε to 15 units and the increase in π_κ, up to 2.7 units. The stable starting of diesel engines of basic design may be maintained even under non-standard conditions ($\varepsilon \geq$ 14–14.5 units), and one-step supercharging ($\pi_\kappa \leq$ 3.5-4.0) may be used.

In fact, with the imposed restrictions P_{max}, ε and π_κ, the loading of a non-cooled piston according to the mean indicated pressure up to P_{mi} = 1.4 MPa and P_{mi} = 1.6 MPa cannot be achieved because the use of $\alpha \approx 2.2$ units and 2.3 units is accompanied by the reduction of ε to 13.5 and 12.5 units and the increase in $\pi_{\kappa,}$ up to 3.6 and 4.3 units, respectively. The acceptable values of ε and π_κ (modes 6, 8) can be achieved only when cooled pistons are used.

Tab. 1. The alternative parametric combinations for regulating the in-cylinder processes' control in high-powered diesel engines D20 based on P_{mi}

No. of alternative	ε	α	T_t, K	π_κ	P_{mi} (MPa)	η_i	$\alpha^{DET}_{G.m.H}$ (W/m^{2}K)	$T^{DET}_{G.m.H}$ (K)
1	15.3	2.3	840	2.45	0.98	0.456	500	945
2	17	2.15	850	2.25	0.97	0.458	505	960
3	17	1.85	955	2.55	1.2	0.439	560	1055
4	16	1.95	930	2.7	1.2	0.439	555	1030
5	16	1.8	980	2.95	1.39	0.432	595	1080
6	15.3	1.9	950	3.2	1.4	0.435	595	1050
7	15.3	1.85	975	3.5	1.6	0.426	630	1075
8	14	2.1	925	4	1.6	0.428	625	1015

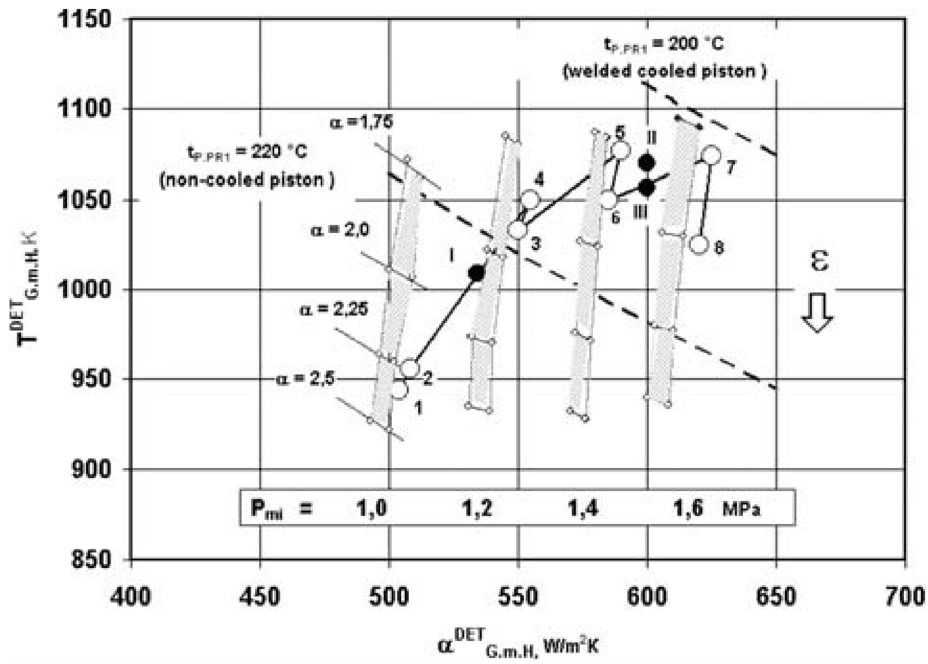

Fig. 4. A complex parametric analysis of the in-cylinder processes and thermal stress in the piston of the basic design engine CHN 15/15 based on P_{mi}: ○ - the increase of P_{mi} and the use of SAC (t_w = 100 °C, the number of test models 1 - 8 correspond to the data given in Tab. 1), ● - a basic design (I- ε = 15.3; P_{mi} = 0.95 MPa, II - ε = 15.3; P_{mi} = 1.17 MPa, III - ε = 14; P_{mi} = 1.17 MPa)

The results obtained in modelling the thermal stressed state of a welded piston presented in Fig. 5 show the efficiency of oil cooling.

The temperature in the area of the first compression ring $t_{P.1PR}$ restricting the loading of diesel engine CHN 15/15 was reduced by 40°C (from 218°C to 178°C) when the cooling by circulation was used. A comparison of the obtained results with the data provided by specialised firms [7, 9] allows us stating that the temperature of the piston seal ring achieved in the present investigation is close to an optimal temperature. The temperature on the surface of the piston head and heat belt was reduced approximately by 20-35°C.

Distribution and intensity of mechanical stresses in the piston body were comparable with those found in its cooled structure. The stresses in the walls of the cooled head end did not exceed 12-15 MPa, whereas the mechanical compression stresses caused by the action of gases were 5-10 MPa.

In general, the lower temperature in all investigated zones of oil-cooled piston positively affected the development of thermal stresses which, for some elements, were by 15-20% lower. The only exception was the remote central area of the inner surface of the piston head, where the value of σ_{DET} remained ~ 52 MPa.

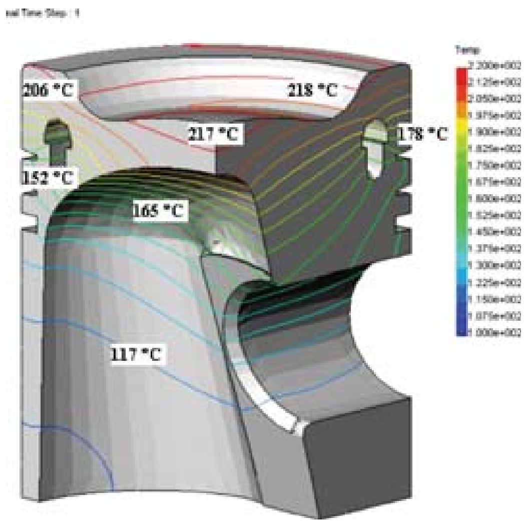

Fig. 5. The temperature field of a cooled welded piston of diesel engine CHN 1515 (with oil feeding and supercharging systems of basic design; cooling by circulation; P_{mi} = 0.96 MPa, n = 2600 min^{-1}, ε = 15.3 units) (see online version for colours)

5. Conclusion

On Basis of the theoretical research and experimental study of high-speed standard size high-powered diesel engines CHN 16.5/18.5, CHN 15/18, CHN 15/15, a system approach to achieving their economical operation (low fuel consumption) and safety has been developed and implemented. Methods of thermal stress analysis of the piston parts based on key parameters (δ, α, ε, T_a, P_a), determining the in-cylinder processes of diesel engines, have been suggested. The described methods are based on calculating mean values of the parameters, characterising heat exchange over the cycle as third type boundary conditions $\alpha_{G.m.H}^{\mathrm{DET}}$ and $T_{G.m.H}^{\mathrm{DET}}$ and their graphical interpretation.

The implemented approach in combination with the results obtained in the analysis of thermal load on piston parts allows us to choose the parameters of in-cylinder processes, taking into account different experimental designs of diesel engines.

A method implemented in diesel engines CHN 15/15 of the basic design with their power increased by 60–70% for P_{mi} = 1.6 MPa.

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