THERMAL EFFECTS OF COATINGS ON THE FRONT SURFACE OF PISTONS. II

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1. Introduction

The thermal effects of coatings applied at the front surface of Diesel engine pistons were examined on heat flux models, by analog and digital simulation.

Our first paper dealt with the method of analog simulation elaborated at the Department of Mechanical and Process Engineering and with the results obtained. The second paper describes the method of digital simulation elaborated at the Department of Chemical Machineries and the results obtained.

2. Application of digital simulation

Analog simulation provided a quick outline of problem solutions and visual reproduction at an accuracy depending on the elements of the network model and on instruments.

Simulation on a digital computer can be of optional accuracy, with boundary conditions variable at will. In view of this latter, the investigations involved exact $t(\tau)$ and $\alpha(\tau)$ values, as well as the highest local heat transfer coefficient $\alpha_{\text{local max}}(\tau)$, characterizing one particular motor.

2.1 *Mathematical model of the problem*

Frontplate of the piston was assumed to accommodate only heat fluxes perpendicular to the front surface.

Differential equations describing the one-dimensional heat transfer:

a) Heat transfer in the coating:

$$\frac{\partial t_B}{\partial \tau} = a_B \frac{\partial^2 t_B}{\partial x^2} \qquad \text{where} \quad 0 < x < L_B . \tag{1}$$

Heat transfer in the piston:

$$\frac{\partial t_D}{\partial \tau} = a_D \frac{\partial^2 t_D}{\partial x^2} \qquad \text{where} \quad L_B < x < L_D. \tag{2}$$

Initial and boundary conditions of (1) and (2):
b) Thermal coupling of the frontplate of the piston and the cylinder space, with a combined convective and radiation heat transfer is given by the boundary condition of the third kind:

$$\frac{\partial t_B}{\partial x} = \frac{\alpha(\tau)}{\lambda_B} [t_B - t(\tau)] \text{ where } x = 0. \tag{3}$$

c) Heat transfer from coating to piston:

$$\lambda_B \frac{\partial t_B}{\partial x} = \lambda_D \frac{\partial t_D}{\partial x} \text{ and } t_B = t_D \text{ where } x = L_B. \tag{4}$$

d) Thermal coupling on the backside of the piston is described by boundary condition of the first kind:

$$t_H = \text{const where } x = L_D. \tag{5}$$

e) Initial condition to the solution of (1) and (2) is given by starting temperature distribution, suitably taken as:

$$t_B = \varphi(x) \text{ and } t_D = \varphi(x) \text{ where } \tau = 0.$$

Solutions of parabolic partial differential equations (1) and (2) satisfying conditions (3) to (6) provide $t_B(x, \tau)$ and $t_D(x, \tau)$ as solutions for the front surface, as well as for temperatures at various depths inside the piston body.

2.2 *Numerical solution*

Above equation system was solved by numerical methods on a digital computer.

For the solution a rectangular point-network was fixed in the domain of independent variables (Fig. 1) and the partial derivates were approximated by finite differences.

The points of the network were chosen near enough to each other to suit the convergence and stability requirements of numerical calculation.

Rewriting (1) and (2) by finite differences, the internal points of the point network:

$$t_{i,j+1} = \left[1-2a_B \frac{\Delta\tau}{(\Delta x)^2}\right] t_{i,j} + a_B \frac{\Delta\tau}{(\Delta x)^2} [t_{i-1,j} + t_{i+1,j}] \tag{6}$$

where $0 < i < n$.

$$t_{i,j+1} = \left[1-2a_D \frac{\Delta\tau}{(\Delta x)^2}\right] t_{i,j} + a_D \frac{\Delta\tau}{(\Delta x)^2} [t_{i-1,j} + t_{i+1,j}] \tag{7}$$

where $n < i < m$.

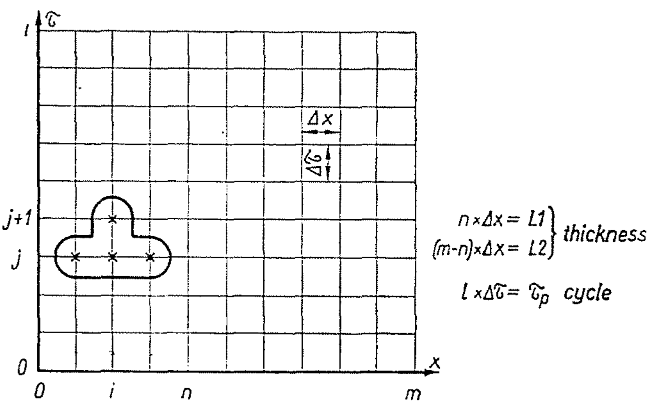

Fig. 1. Rectangular point network applied to the numerical treatment

The surface temperature gradient was obtained by approximating the temperature values near the surface by a second-grade polynomial producing numerically

$$\left.\frac{\partial t_B}{\partial x}\right|_{x=0}.$$

Thus boundary conditions (3) numerically:

$$t_{0,j+1} = \frac{\frac{2(\Delta x)\alpha_{j+1}}{\lambda_B} t_{j+1} + 4t_{1,j+1} - t_{3,j+1}}{2(\Delta x)\left[\frac{\alpha_{j+1}}{\lambda_B} + 3\right]}. \tag{8}$$

To meet boundary condition (4), temperature values $t_{n-1,j+1}$, and $t_{n+1,j+1}$ were approximated by the first three elements of Taylor polynomial.

In form of finite differences:

$$t_{n,j+1} = \left[1 - \frac{2a_B\left(1+\frac{\lambda_B}{\lambda_D}\right)\frac{\Delta\tau}{(\Delta x)^2}}{\frac{a_B}{a_D}+\frac{\lambda_B}{\lambda_D}} \right] t_{n,j} + \\ + \frac{2a_B\left(1+\frac{\lambda_B}{\lambda_D}\frac{\Delta\tau}{(\Delta x)^2}\right)}{\frac{a_B}{a_D}+\frac{\lambda_B}{\lambda_D}} \left(t_{n+1,j}+\frac{\lambda_B}{\lambda_D}t_{n-1,j}\right) \tag{9}$$

Eqs (6) to (9) determined from the mathematical model gave $t(x, \tau)$ values according to the so-called explicit scheme.

Calculation follows the flow chart in fig. 2.

K stands for the number of periods, H for the intervals, where temperature values will be printed.

The knowledge of periodically varying $\alpha(\tau)$ and $T(\tau)$ is needed.

Tests involved $\alpha(\tau)$ and $t(\tau)$ values shown in Fig. 3 and 4. The values of

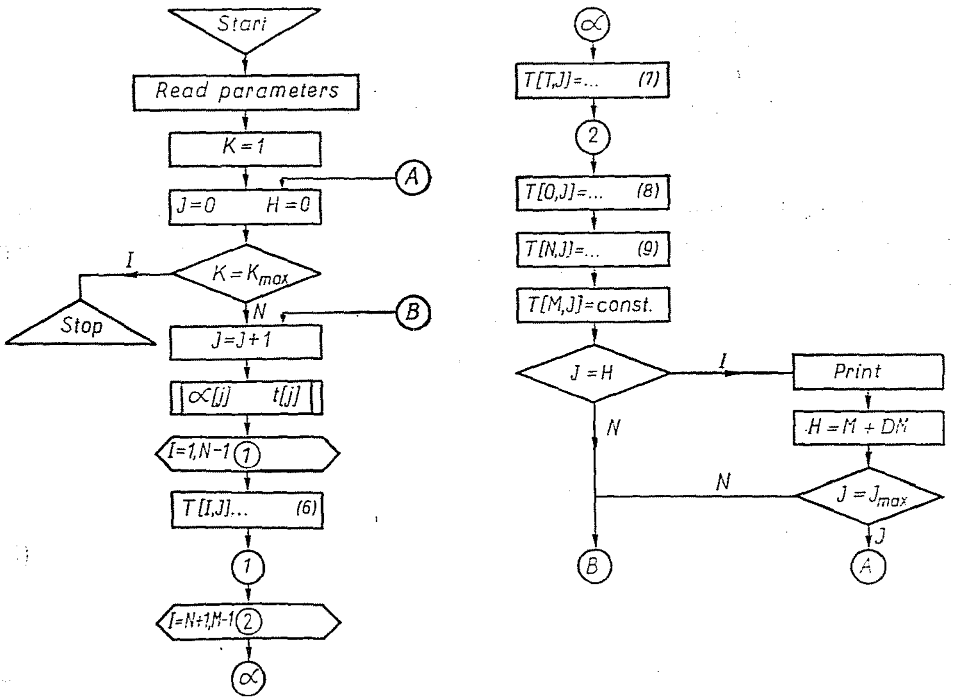

Fig. 2. Flow chart of computation

α_{j+1} and t_{j+1} were selected by the program from the data of the diagram at time $(j+1)\Delta\tau$.

At start,

$$\tau = 0; \; t_B = \varphi_1(x); \quad \text{and} \quad t_D = \varphi_2(x);$$

temperature distribution can be specified at will as steady conditions set in always at the same value. Allocation of $t = \varphi(x)$, however, significantly influences the running time until steady condition.

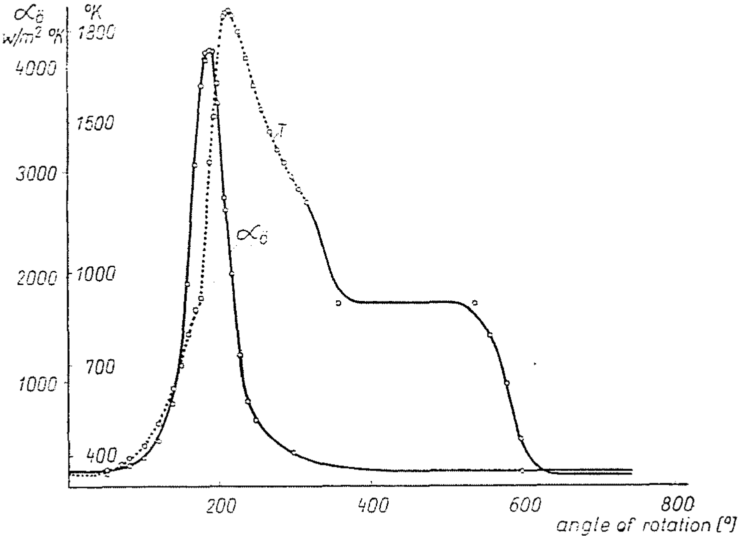

Fig. 3. Temperature in the cylinder vs. time and average, combined heat transfer coefficient vs. time

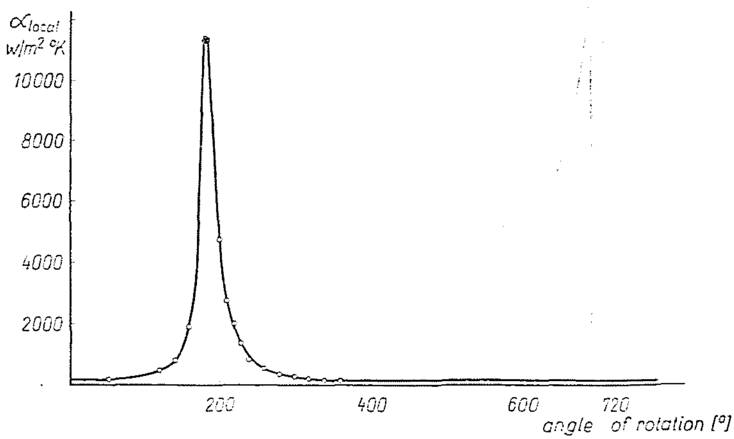

Fig. 4. Local highest heat transfer vs. time

2.3 *Outputs*

Simulation referred to a Diesel engine of $n = 1500$ r.p.m., that is period time $\tau_t = 0.08$ with pistons of a certain coating. Influence of various coating thicknesses was investigated.

Characteristics of material:

$\lambda_B = 17$ kcal/m h grad
$\lambda_D = 116$ kcal/m h grad
$c_B = 0.125$ kcal/kg grad
$c_D = 0.214$ kcal/kg grad
$\varrho_B = 7900$ kg/m^3
$\varrho_D = 2751$ kg/m^3

Thickness of piston frontplate: $L_D = 15$ mm
Investigated coating thickness: $L_B = 1;\ 0.5;\ 0.05$ mm
Backside-temperature of piston frontplate $t_H = 200$°C

Figs 5 to 12 plotted from outputs show development of maximum and minimum temperature on the piston frontplates both without coating, and with coatings of various thicknesses. Both average heat transfer coefficients and local maxima are indicated. Results for the coating of 0.05 mm thickness are only approximate because of computation techniques.

As an example, Fig. 13 shows surface temperature vs. time of a plate without coating and in case of average temperature transfer.

Numerical differences of maximum to minimum temperatures have been compiled in Table 1. A depth is seen to be in the material, where the temperature fluctuation is still perceptible.

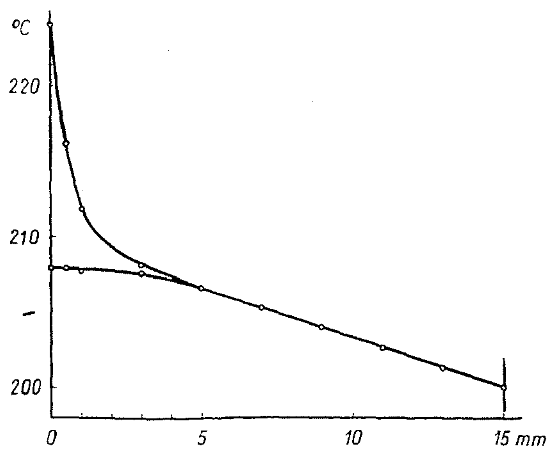

Fig. 5. Temperature maxima and minima on piston frontplate without coating, for α_{average}

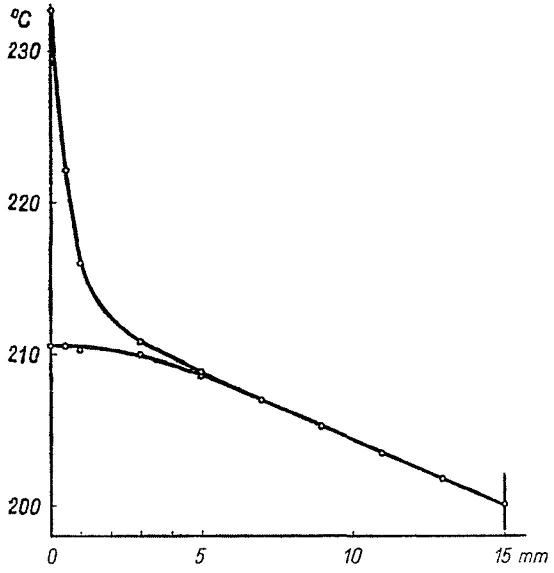

Fig. 6. Temperature maxima and minima on piston frontplate without coating, for $\alpha_{\text{local max}}$

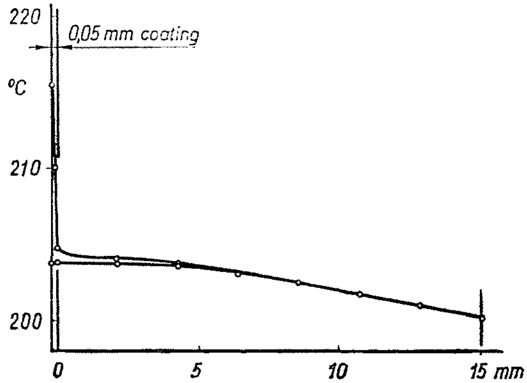

Fig. 7. Temperature maxima and minima on piston frontplate with a coating of 0.05 mm for α_{average}

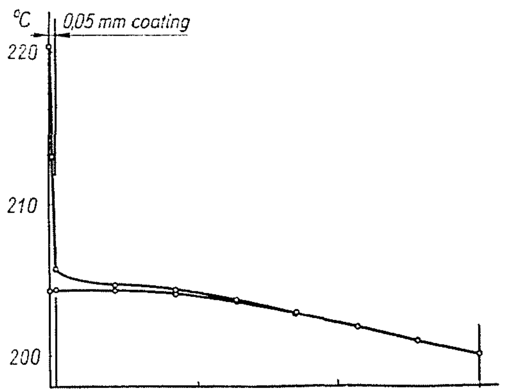

Fig. 8. Temperature maxima and minima on piston frontplate with a coating of 0.05 mm, for $\alpha'_{\text{ocal max}}$

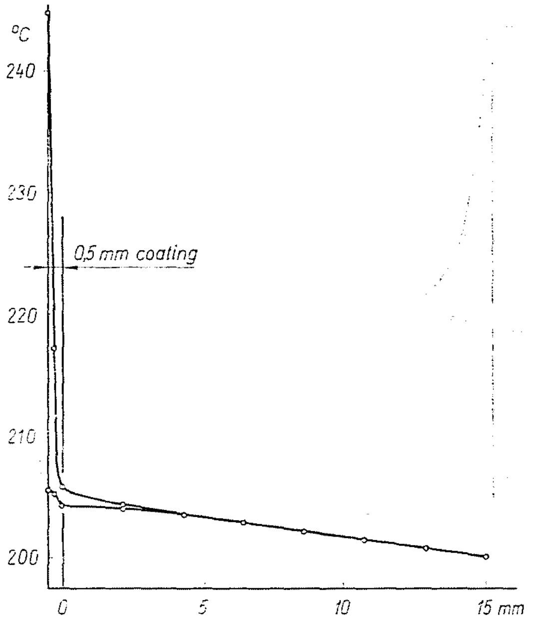

Fig. 9. Temperature maxima and minima on piston frontplate with a coating of 0.5 mm for $\alpha_{average}$

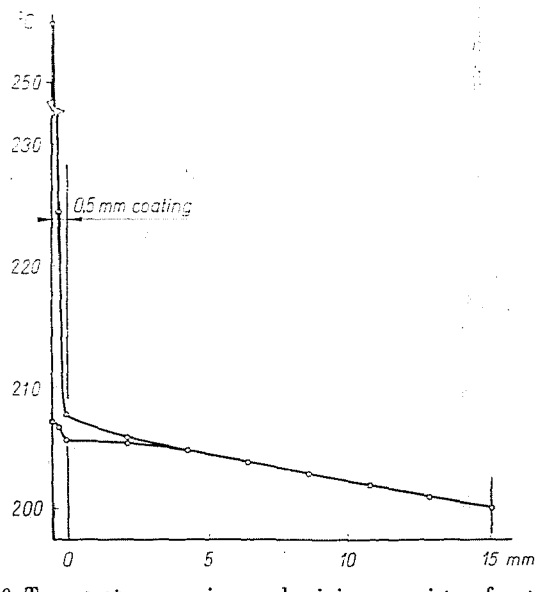

Fig. 10. Temperature maxima and minima on piston frontplate with a coating of 0.5 mm, for $\alpha_{local\ max}$

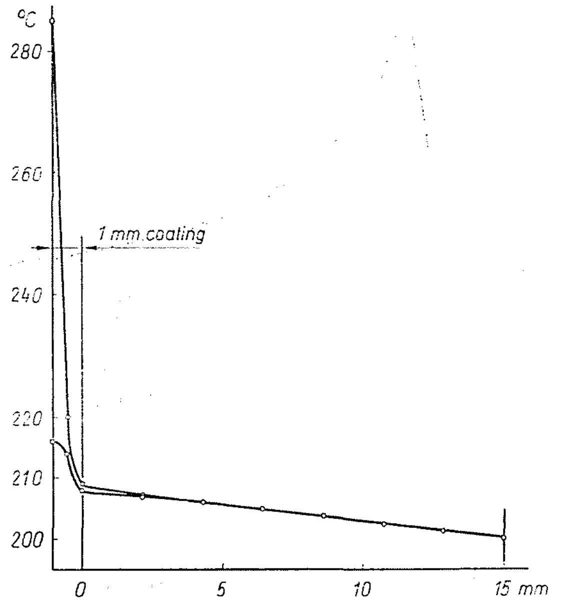

Fig. 11. Temperature maxima and minima on piston frontplate with a coating of 1 mm, for $\alpha_{average}$

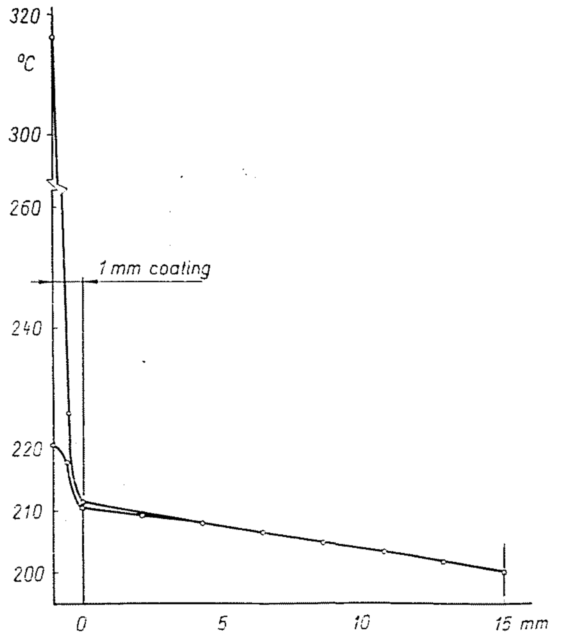

Fig. 12. Temperature maxima and minima on piston frontplate with a coating of 1 mm, for $\alpha_{local\ max}$

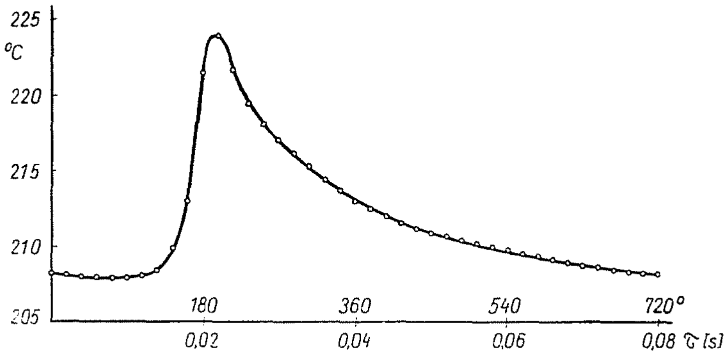

Fig. 13. Cyclic surface temperature vs. time, on piston frontplate without coating, for $\alpha_{average}$

Table 1

Heat transfer coefficient	Coating thickness L_B[mm]	Serial number of the point numbered from the front surface Δt_{max} [°C] 0	1	2	3	4	5	6	7	8	9
$\alpha_{average}$	0	16.10	8.29	3.10	0.55	0.08	0.01	0.01	0.00	0.00	0.00
	0.05	11.76	6.38	0.96	0.22	0.19	0.14	0.08	0.05	0.02	0.00
	0.5	39.46	12.22	1.53	0.19	0.03	0.01	0.01	0.00	0.00	0.00
	1	18.12	6.21	0.71	0.09	0.02	0.00	0.00	0.00	0.00	0.00
α_{local} max.	0	22.16	11.63	5.65	0.77	0.12	0.02	0.01	0.00	0.00	0.00
	0.05	15.82	8.73	1.31	0.24	0.21	0.16	0.10	0.05	0.02	0.00
	0.5	47.68	17.62	2.26	0.27	0.02	0.01	0.01	0.01	0.00	0.00
	1	95.40	8.32	0.94	0.13	0.02	0.00	0.00	0.00	0.00	0.00

Results show on uncoated surfaces temperature fluctuations of 16 to 22 °C, this reduced to 1 to 2 °C already by a fine coating layer. On the contrary, surface temperature of the coating fluctuated more than that of the surface without coating and this effect intensified when coating was thicker.

Thick coatings exhibited high surface temperature variations imposing as increased thermal stresses on it and leads to thermal expansion resulting in flaking off for such thick layers.

The coating slightly modifies the average temperature of the piston metal.

Summary

Thermal effects of coatings of various thicknesses applied at the front surface of pistons of Diesel engines were examined by means of digital simulation. An unidimensional heat conduction, perpendicular to the frontplate was assumed and investigations affected one particular type of coating, a gas temperature vs. time characteristic of a given operating condition of the engine, and a combined heat transfer coefficient vs. time.

Computations showed the temperature fluctuations of 16 to 22 °C of the piston frontplate surface without coating, which could be reduced to 1 to 2 °C by a fine coating layer. Increased coating thicknesses are more efficient moderators, but increased temperature fluctuation appeares on the surface of the coating and this may overstrain the coating layer itself.

Acknowledgement

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Notations

a_B	thermal conductivity coefficient of coating material [m^2/h, m^2/s]
a_D	thermal conductivity coefficient of piston frontplate material [m^2/h]
c_B	specific heat of coating material [kcal/kg grad]
c_D	specific heat of piston frontplate material [kcal/kg grad]
L_B	thickness of coating [m; mm]
L_D	thickness of piston frontplate [m, mm]
t	temperature inside the piston cylinder [°C, °K]
t_B	temperature of the coating [°C, °K]
t_D	temperature in the piston frontplate [°C, °K]
t_H	temperature on the backside of the piston frontplate [°C, °K]
x	local co-ordinate perpendicular to the plate [m]

Greek letters

α	compound heat transmission coefficient $\alpha = \alpha(\tau)$. [kcal/m^2 h grad, W/m^2 grad]
$\varphi(x)$	starting place-dependent temperature distribution [grad]
λ_B	heat conduction coefficient of coating material [kcal/m h grad]
λ_D	heat conduction coefficient of piston frontplate material [kcal/m h grad]
ϱ_B	density of coating layer [kg/m^3]
ϱ_D	density of piston metal [kg/m^3]
τ	time [s, h]
τ_t	cycle [s]

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