EXAMINATION OF THE THERMAL EFFECT OF COATINGS APPLIED TO THE FRONT SURFACE OF PISTONS

PART I

By

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Introduction

The thermal effect of coatings applied to the front surface of the pistons of Diesel engines were examined by the method of analog and of digital simulation on heat flux models.

Our first paper dealt with the method of analog simulation as elaborated at the Department of Mechanical and Process Engineering and its results. The second paper will discuss the method of digital simulation elaborated at the Department of Chemical Machines and the results obtained.

1. Application of the analog simulation

Assuming a given geometry and boundary conditions, — the time function $t_f = t(\tau)_f$ of the surface temperature of pistons with and without coating, as well as that of the temperatures in various depths measured from the front surface of pistons ($t_d = t(\tau)_d$) had to be established.

1.1 *The heat flux network model*

The efficiency of applying the heat flux network models decisively depends on the proper design of the model. On the basis given of data the following assumptions were made for the model:

a) In the front plate of the piston there are only heat fluxes perpendicular to the front surface.

b) The coating applied to the piston is a π-element with concentrated parameters.

c) To observe the damping of the thermal oscillation, the front plate of the piston is "cut into layers" by increasingly fine divisions, and each layer is a Γ-element with concentrated parameters. The divisions (thicknesses of the layers) for a piston as an example are shown in Fig. 1 and Table 1.

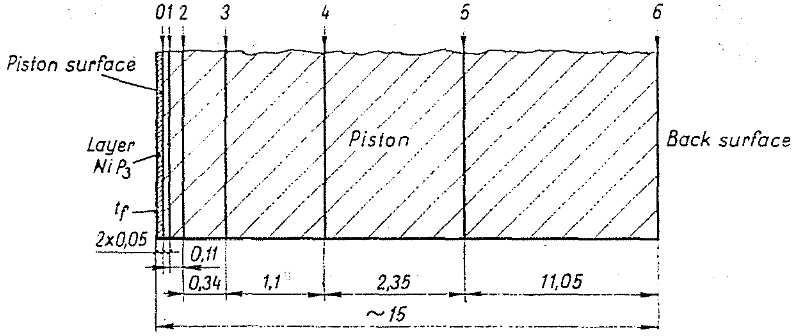

Fig. 1. Segmentation layers of the piston front plate. The numbered arrows pointing downwards mark the boundaries of the layers

Table 1

Division spacing of the parallel segmentation layers of the front plate

Layer mark	Thickness	Layer mark	Thickness
v_B	$5 \cdot 10^{-2}$ mm	v_4	1.1 mm
v_1	$5 \cdot 10^{-}{}_{2}$ mm	v_5	2.35 mm
v_2	$11 \cdot 10^{-2}$ mm	v_6	11.05 mm
v_3	$34 \cdot 10^{-2}$ mm		

d) The time function of the temperature of the gas in the cylinder space is illustrated in Fig. 2; it is modelled (simulated) by means of an analog *voltage generator.*

e) The thermal interconnection of the front surface of the piston with the combustion gases in the cylinder space is interpreted as a compound con-

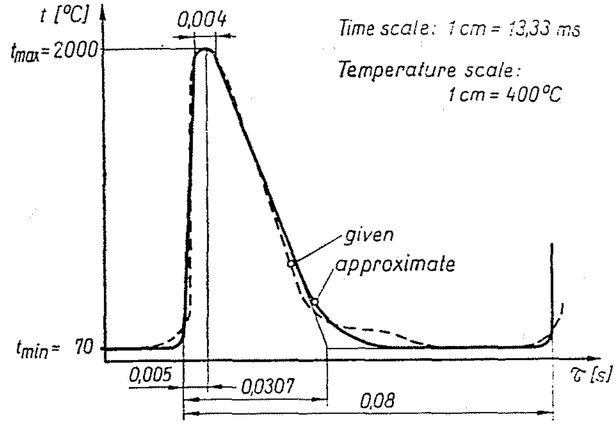

Fig. 2. Time function of the gas temperature in the cylinder

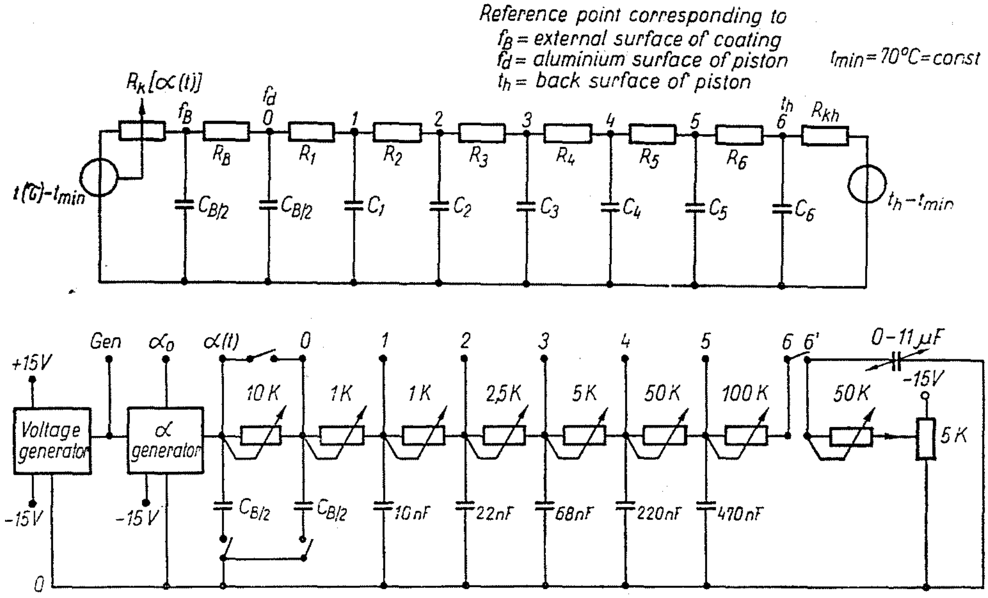

Fig. 3. a) Design of the heat-flux network model of the piston front plate; b) circuits of the constructed model

vective effect, given by the 3rd kind boundary condition. The overall heat transfer coefficient is dependent on temperature and time. The character of its change is regarded as nearly proportional to the temperature-time function of the gas (according to Fig. 2). To model (simulate) the overall heat transfer coefficient, an *α-generator* was applied.

f) Also the back surface of the front plate of the piston is connected to the ambiency of constant temperature with the 3rd kind boundary condition. Due to the overall heat transfer coefficient of high value, the coupling will be similar to the effect of the first kind boundary condition.

The analog network model of the thermal processes taking place in the front plate of the piston — in accordance with the above model assumptions — is illustrated in Fig. 3.

1.2. *Elements of the heat flux network model*

Passive elements

The values of the passive elements in the heat flux network model are given in Table 2. The heat conduction resistances $\left(R_t = \frac{v}{\lambda A}\right)$ of the layers of surface unit ($A = 1$ m^2) are found in column 1. On the basis of the resistance scale $a_R = \frac{R_t}{R_v} = 2{,}04 \cdot 10^{-9} \frac{°C/W}{\Omega}$, column 2 gives the corresponding analog electrical resistances. The values of the layer heat capacities ($C_t = mc$, $m = \varrho v A$) for a surface unit ($A = 1\ \mathrm{m}^2$, $C_t = \varrho v c$, c: J/kg °C) are contained in column 3, and the analog electrical capacities, calculated with the analog electrical capacitance scale $a_c = \dfrac{C_t}{C_v} = 1{,}31 \cdot 10^{10}\ \dfrac{J/°C}{F}$, are given in column 4. In Fig. 3b the actual values of the elements of the analog network model are indicated.

Table 2

Values of the passive network elements of the heat-flux network model

Place	1 R_t °C/Wm²	2 R_v Ω/m²	3 C_t J/°Cm²	4 C_v nF/m²
Coating	$10.75 \cdot 10^{-6}$	5 260	125.5	10.0
	$3.58 \cdot 10^{-6}$	1 755	251.0	20.0
			553.0	44.0
1. layer	$4.1 \cdot 10^{-7}$	201	131.0	10
2. layer	$9.02 \cdot 10^{-7}$	442	288.0	22
3. layer	$27.9 \cdot 10^{-7}$	1 368	891	68
4. layer	$90.2 \cdot 10^{-7}$	4 420	2 880	220
5. layer	$192.5 \cdot 10^{-7}$	9 440	6 160	470
6. layer	$906 \cdot 10^{-7}$	44 700	29 100	2230

The time scale of the analog system is $a_\tau = a_R \cdot a_c = 26.6$, yielding for the time parameter of the analog model $\tau_v = \dfrac{\tau_t}{a_\tau} = 3 \cdot 10^{-3}$ s, where $\tau_t = 0.08$ s is the period time in our example.

The analog voltage generator of the temperature

The approximative analog voltage-time function of the function $t(\tau)$ according to Fig. 2 was produced by means of a signal generator consisting essentially of three units.

The basic signal is delivered by an astable *square signal generator* of variable frequency and duration factor. This voltage signal comes to an *integrator* which converts it into an asymmetric sawtooth voltage. A *level cutter* and a *low-pass filter unit* remove the upper peak and the lower portions of the sawtooth signal, and "round off" its corners, thus giving it a shape nearly identical with the required temperature-time curve. To avoid the reverse effects coming from the load, an input was formed, of a very small impedance as compared with the coupled network. The period time as well as the slope of the rising and falling portions can be tuned (Fig. 4).

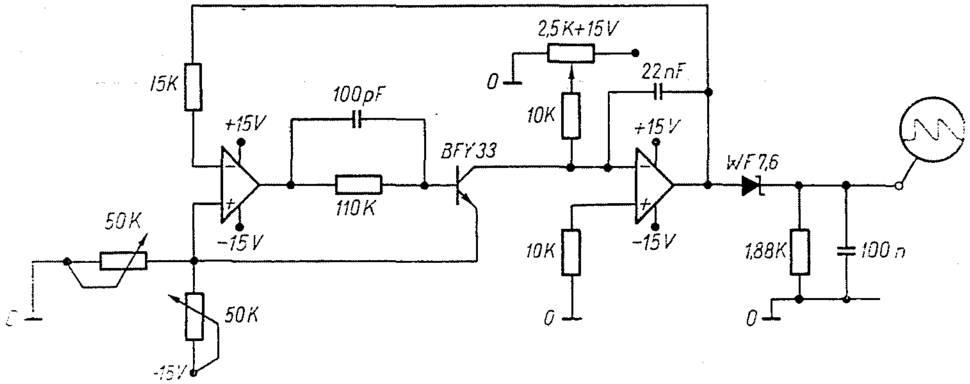

Fig. 4. Scheme of the analog signalling voltage generator

The α-generator

According to model condition e), the task of the α-generator simulating the thermal coupling between the cylinder space and the front surface of the piston can be accomplished by a resistor controlled by a voltage corresponding to the temperature of the cylinder space. During the examinations it was desired to change the maximum and minimum values of the overall heat transfer coefficient. The heat transfer coefficient varying between the two limit-values was produced by an earthed gate electrode circuit of a field effect transistor. The maximum heat transfer coefficient (minimum heat transfer resistance) was adjusted by means of a potentiometer connected in series (Fig. 5).

The thermic coupling of the back surface of the piston front plate was simulated by a resistor connected to the analog voltage level corresponding to the temperature t_h of the back surface. The analog voltage of the back surface temperature was produced by means of a voltage divider, of a considerably lower internal resistance than the heat transfer resistance.

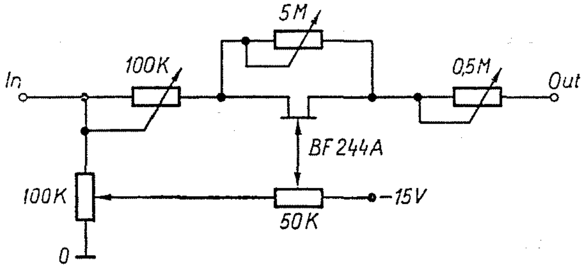

Fig. 5. Scheme of the α-generator

Table 3

Data combinations adjusted

Parameters		Measure-							
		1	2	3	4	5	6	7	8
λ_B kcal/mh °C	1				x	x	x		
	12							x	x
	∞	x	x	x					
C_B kcal/kg °C	0	x	x	x					
	0.12				x			x	
	0.24					x			x
	0.528						x		
t_h °C	170		x						
	200	x			x	x	x	x	x
	230			x					
α_{max} kcal/m^{2}h °C	1 480	x	x	x	x	x	x	x	x
	7 400								
	14 800								

1.3. *The measuring system and the measurements*

The analog model-network was operated by stabilized D.C. (Fig. 6). A digital multimeter was used to measure the resistance, and a double-relay oscilloscope to examine the measuring signals.

After adjustment of the resistors and signal patterns, measurements were carried out with various data combinations, which allowed conclusions on the effects of various sorts of coatings. Fig. 7 shows the generator signal of the time-function $t(\tau)$ of the gas temperature. The maximum of the overall heat transfer coefficient α, characteristic for the thermal coupling with the cylinder space, was assumed for various values, since — in our opinion — a considerable uncertainty must be reckoned with in the judgement of the extreme values for the overall heat transfer coefficient (α_{max} and α_{min}). This uncertainty is due on the one hand to the global consideration of the flame radiation and, in general, of the quota fraction of radiation heat transfer. On the other hand, due to the impact of the gas + fuel mixture flowing from the antechamber at a high speed, with the piston surface opposite to the anteduring the measurements

ment No.										
9	10	11	12	13	14	15	16	17	18	19
	x	x	x	x	x	x	x	x		
x										
									x	x
	x				x				x	x
		x				x				
			x				x			
x				x				x		
x	x	x	x	x	x	x	x	x	x	x
x										
		x	x	x	x				x	
					x	x	x	x		x

chamber, as well as in connection with temporary burning in the boundary layers, — local peak temperatures may arise. It is doubtful whether all these effects can be described exactly with the use of an overall heat transfer coefficient assumed between fixed limits. Taking all these into consideration, the signal generator producing the time-function of the heat transfer coefficient was designed in a way permitting to vary the values of $\alpha_{\max}$, and the measurements were carried out also with the values of $\alpha_{\max}$ given in the last three columns of Table 3.

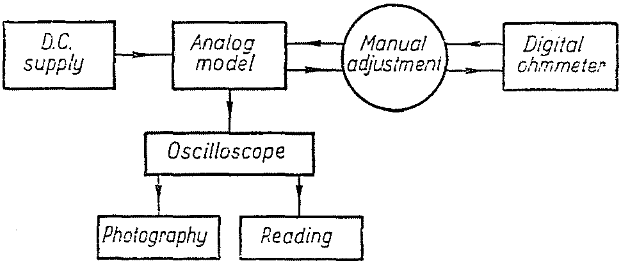

Fig. 6. Flow chart of the measuring system

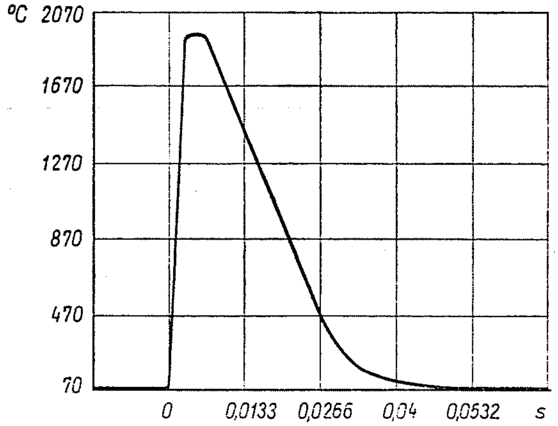

Fig. 7. Generator-signal of the time-function $t(\tau)$ of gas temperature in the cylinder space (photo taken from the oscilloscope)

1.4. *Results and discussion*

The results of the measurements are summarized in Tables 4 . . . 7.

Table 4

Measurement results with various values of $\alpha_{\max}$

°C	Without coating			Wiht coating		
	$\alpha_{\max}$ kcal/m² h °C					
	1480	7400	14800	1480	7400	14 800
Measurement No	1	18	19	5	12	18
t_B max	—	—	—	254.7	456	676
t_B min	—	—	—	216.7	290	350
Δt_B	—	—	—	38.0	166	326
t_0 max	236.5	390	530	230.7	354	478
t_0 min	218.5	302	362	217.7	294	354
Δt_0	18.0	88	168	13	60	124
t_1 max	234.5					
t_1 min	218.4					
Δt_1	16.0					
t_2 max	232.3					
t_2 min	218,3					
Δt_2	14					
t_3 max	228.0	Deviations of heat distribution in the inner layers of the piston can be concluded on by proportional scaling starting from the maximum as in column 1.				
t_3 min	218.0					
Δt_3	10.0					
t_4 max	220					
t_4 min	217					
Δt_4	3					
t_5 max	215.2					
t_5 min	214.7					
Δt_5	0.5					
t_6 max	200	200	200	200	200	200
t_6 min	200	200	200	200	200	200

Table 5

Temperature values on the front surface of the piston front plate, without and with coating, respectively

°C	$\alpha_{max} = 1480$ (kcal/m² h °C)		$\alpha_{max} = 7400$		$\alpha_{max} = 14\,800$	
	with coating	without coating	with coating	without coating	with coating	without coating
Measurement No.	5	1	12	18	16	19
$t_{0\,max}$	230.7	236.5	354	390	478	530
$t_{0\,min}$	217.7	218.5	294	302	354	362
Δt_0	13	18	60	88	124	168

Table 6

Effect of the material characteristics (specific heat capacity, heat conductivity) upon the temperature of the front surface

	$\lambda_B = 4$ kcal/m h °C			Heat conductivity of the coating $\lambda_B = 12$ kcal/m h °C		
	Specific heat of coating (kcal/kg °C)			Specific heat of coating (kcal/kg °C)		
	0.12	0.24	0.528	0.12	0.24	0.528
Measurement No.	4	5	6	7	8	9
$t_{B\,max}$	259.0	254.7	246.5	243.1	242.1	239.0
$t_{B\,min}$	217.0	216.7	216.5	218.1	218.1	218.0
Δt_B	42.0	38.0	30.0	25.0	24.0	21.0
$t_{0\,max}$ (°C)	232.8	230.7	227.6	233.1	231.1	228.0
$t_{0\,min}$	217.8	217.7	217.6	218.1	218.1	218.0
Δt_0	15.0	13.0	10.0	15.0	13.0	10.0

Table 7

Effect of the specific heat capacity of the coating upon the temperature of the front surface for different heat transfer coefficients

	$\alpha_{max} = 1480$ kcal/m² h C°			$\alpha_{max} = 7400$				$\alpha_{max} = 14\,800$			
	Specific heat of coating (kcal/kg °C)			specific heat				Specific heat			
	0.12	0.24	0.528	0	0.12	0.24	0.528	0	0.12	0.24	0.528
Measurement No.	4	5	6	10	11	12	13	14	15	16	17
$t_{B\,max}$ (°C)	259	254.7	246.5	478	468	456	430	678	676	676	670
$t_{B\,min}$	217	216.7	216.5	286	288	290	294	350	350	350	350
Δt_B	42	38	30	192	180	166	136	328	326	326	320
$t_{0\,max}$	232.8	230.7	227.6	362	358	354	343	478	478	478	478
$t_{0\,min}$	217.8	217.7	217.6	288	290	294	298	354	354	354	354
Δt_0	15	13	10	74	68	60	45	124	124	124	124

Table 8

Effect of the back surface temperature t_h of the piston front plate upon the front surface temperature of the piston, without coating ($t_0 = t_{fd}$)

	Temperature of back surface, (t_h,°C)		
	170	200	230
Measurement No.	2	1	3
$t_{0\ \max}$ (°C)	208	236.5	262
$t_{0\ \min}$	189	218.5	245
Δt_0	19	18	17
$t_{1\ \max}$	205.8	234.5	259.9
$t_{1\ \min}$	188.8	218.4	244.9
Δt_1	17	16	15

Tables 4 and 5 demonstrate that the temperature t_1 of the piston surface but slightly changes upon the effect of the coating in the cases with and without a layer, when $\alpha_{\max} = 1480$ kcal/m^2 h °C (1720 W/m^2 °C). When a coating is applied, then — due to its heat conductive resistance — a smaller heat flux flows through the piston than without coating ($t_0 = t_{fd}$ is lower and t_{fB} is higher than without a coating).

Due to the heat capacity of the coating, the fluctuation of the surface temperature t_{fB} is smaller than the t_{fd} without coating. A deviation decisive for the thermal fatigue of the piston surface occurs, however, only in the case of $\alpha_{\max} > 7000$ kcal/m^2 h °C (8140 W/m^2 °C). The temperature oscillation inwards the piston subsides rapidly. Aback from the 4th layer the effect of pulsation practically disappears, and the temperature of the piston can be regarded as constant in time (curves a, d in Fig. 8).

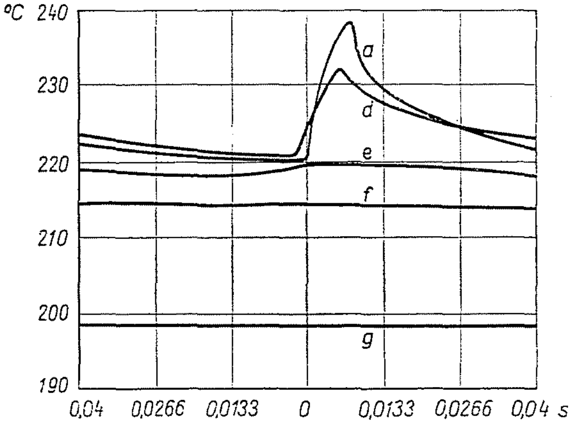

Fig. 8. The change in time of the piston temperature without coating, in the different layers, according to oscilloscope photos (Curves: a: place 0; d: place 3; e: place 4; f: place 5; g: place 6)

Summary

The likely thermal effect of coatings applied to the front surface of the pistons of Diesel engines was examined by means of an analog electrical model of a heat flux network. Heat conduction perpendicular to the front plate was assumed for the case of a given time function of the gas temperature, as well as for the time function of the overall heat transfer coefficient, with various data systems.

The results of the measurements have demonstrated that the thermal effect of the coating upon the temperature level of the piston front surface and its oscillation becomes significant in the case when $\alpha_{max} > 7000$ kcal/m^2 h °C (8140 W/m^2 °C).

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