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STANISŁAW JĘDRZEJOWSKI[*)]

APPLICATION OF ERODING THERMOCOUPLES IN EXPERIMENTAL DETERMINATION OF UNSTEADY HEAT FLUX INSIDE A COMPRESSOR CYLINDER

The knowledge of heat transfer processes inside a compressor cylinder is very important from the technical point of view. An adiabatic model of compression can be assumed in theoretical investigations. In practice, the compressor cylinder is always cooled to decrease the compression work and to reduce the final temperature of a medium being compressed.

This paper presents applications of the NANMAC eroding thermocouples to record temperature time histories of surfaces taking a part in the heat exchange during the compression cycle. The thermocouple construction and junction technology ensure a very small thermal inertia. The response time is of the order of 10 μs.

The eroding thermocouple was used to measure an instantaneous surface temperature of a plate closing the cylinder and the piston head temperature. Because of very low value of the thermoelectric signal, an amplifier of a very high gain and reasonable bandwidth was required. This induced noise of significant amplitude. The recorded experimental data were numerically processed in order to exclude the noise of measurement circuits, and then the data were used to calculate local heat flux rates. To ensure repeatability of the measurements, the experiments were carried out in a specially prepared set-up allowing single compression cycles to be performed.

Nomenclature

a – thermal diffusivity,
c – heat capacity,
q – heat flux density,
T – temperature,
t – time,
x – distance,
i, k, n – time step numbers,
δ – penetration depth,
λ – heat conductivity,
ρ – density,
τ – variable of integration, time,
ω – angular frequency.

*) *Department of Thermal Technology and Refrigeration, Technical University of Lodz, Stefanowskiego 1/15, 90-924 Łódź, Poland; E-mail: sjedrzej@cksg.p.lodz.pl*

1. Introduction

A method of measuring temperature time histories on the heat transfer surface was used in the investigations of heat transfer in the compressor cylinder described below. The measurements were performed on the inner surface of the plate closing the cylinder and on the piston head. The recorded temperature histories were used to calculate local heat flux rates.

A surface thermocouple (Nanmac Corporation, USA) was used in the investigation. This was a jacket-type thermocouple with an exposed junction, formed due to mechanical erosion of the electrodes materials during grinding the sensor tip with abrasive paper. The junction was very thin and therefore the sensor was characterised by a short response time of order of 10 μs [4]. Because of the method of the junction formation, these thermocouples are called eroding thermocouples. The method of mounting of the thermocouple in the wall is described in chapter 3 of this paper.

2. Theoretical basis

Heat transfer inside the compressor cylinder is unsteady, although it is repeated periodically because of the device operation cycles. On the side of the working agent, it is a forced convection of significant turbulence which, in the case of a combustion engine, is overlapped by the radiation of flame and combustion gas. Heat transferred to the walls encasing the working chamber causes a variable temperature field in the solid body of complex geometry.

The periodicity of the phenomena taking place in the cylinder suggests that it is possible to observe time-averaged effects of heat transfer. Due to fast operation of modern piston machines and significant heat capacities of metal elements, the averaging could be done in a relatively short time. In practice, however, long time is needed to obtain such conditions. The level on which time-averaged conditions of heat transfer are set up depends on the machine operating conditions, e.g. rotational speed or loading.

In majority of piston machines, a mean temperature of the working agent is higher than the ambient temperature. This determines the global direction of heat transfer from the agent to the outside. Only in expanders and compressed-air engines will the direction of heat flow be reversed. Determination of the amount of exchanged heat requires an energy balance of the investigated object. This can be performed for the whole machine, but because of the order of magnitudes, which are involved in the balance, it would be burdened with a serious error. The separation of the working chamber is hardly possible.

One of the methods for determination of heat flux on the wall surface relies on the recording of this surface temperature. A variable heat flux acting upon the element being investigated causes changes in the temperature field inside the body according to the theory of unsteady heat conduction. Due to heat capacity of the wall material, temperature changes decrease as the heat penetrates deeper into the body. The term "heat penetration depth" in time t is defined as [2]:

$$\delta = \sqrt{at} \ . \tag{1}$$

The so defined value of δ results from relating the Fourier number to unity.

For quickly changing heat flux, the penetration depth is small. Depending on the material properties and the process duration, it ranges from a tenth part to several millimetres (Table 1). For so small penetration depths, the heat transfer in a wall of sufficient thickness may be considered as one-dimensional unsteady heat conduction in a flat semi-infinite body. This problem is described by the equation:

$$\frac{\partial T}{\partial x} = a \frac{\partial^2 T}{\partial x^2}, \tag{2}$$

with the following initial and usteady boundary conditions:

$$\begin{aligned} &\text{at} \quad x \geq 0 \quad \text{and} \quad t = 0, \quad T = T_0, \\ &\text{at} \quad x = 0 \quad \text{and} \quad t > 0, \quad T = T_0(t). \end{aligned} \tag{3}$$

Table 1.

Thermal properties and penetration depths of temperature wave for different materials

Material	λ W/mK	ρ kg/m^3	c kJ/kgK	$a \cdot 10^6$ m^2/s	δ_1 (t = 0.2 s) mm	δ_2 (t = 0.2 ms) mm
Aluminium	238	2696	0.917	96.3	4.4	0.140
Constantan	23	8920	0.410	6.1	1.1	0.035
Copper	397	8960	0.386	114.8	4.8	0.150
Nickel	89	8900	0.452	22.0	2.1	0.066
Platinum	72	21450	0.134	24.8	2.2	0.069
Steel	50	7840	0.456	14.2	1.7	0.054
Stainless steel	19	7860	0.461	5.3	1.0	0.032
Tungsten	174	19300	0.138	65.3	3.6	0.110
Gold	316	19300	0.130	126.0	5.0	0.160

In this case, Duhamel's theorem should be used to obtain a solution. The problem with unsteady boundary conditions can be solved on the basis of the solution of the problems with steady conditions. Duhamel's theorem and numerous examples of its applications can be found, for example, in [1].

We are looking for a solution in the form of the sum:

$$T = u + v, \tag{4}$$

where u is the solution of the conduction equation with the boundary conditions:

$$\begin{aligned} &\text{at} \quad x \geq 0 \quad \text{and} \quad t = 0, \quad u = T_0, \\ &\text{at} \quad x = 0 \quad \text{and} \quad t > 0, \quad u = 0, \end{aligned} \tag{5}$$

and v is the solution with the following boundary conditions:

$$\begin{aligned} &\text{at} \quad x \ge 0 \quad \text{and} \quad t = 0, \quad v = 0, \\ &\text{at} \quad x = 0 \quad \text{and} \quad t > 0, \quad v = T_0(t). \end{aligned} \tag{6}$$

The function $T_0(t)$ represents the temperature history on the semi-infinite body surface.

To solve the above problem, the derivative $\left(\dfrac{\partial T}{\partial x}\right)_{x=0}$ is searched for. An instantaneous value of the heat flux rate on the body surface at moment t can be presented as

$$q(t) = \sqrt{\frac{\lambda \rho c}{\pi}} \int_0^t \frac{1}{\sqrt{t-\tau}} \frac{dT}{d\tau} d\tau . \tag{7}$$

A further solution of eq. (7) requires the knowledge of the function $T(t)$ – the surface temperature variability in time. Analytical integration of the above equation is possible only in simple cases. This is feasible particularly when the surface temperature is approximated by the Fourier series:

$$T = T_m + \sum_{k=1}^{n} \left[A_k \cos(k\omega t) + B_k \sin(k\omega t) \right]. \tag{8}$$

Heat flux rate in this case is given by the equation:

$$q = q_m + \sqrt{\lambda \rho c} \sum_{k=1}^{n} \sqrt{\frac{k\omega}{2}} \left[(A_k + B_k)\cos(k\omega t) + (-A_k + B_k)\sin(k\omega t) \right], \tag{9}$$

where q_m is the constant component of heat flux rate. Its value can be determined from the stationary condition of heat conduction induced by average temperature T_m being a constant component of the boundary condition (8).

In experimental studies, the boundary condition does not occur in the form of a function described by equation (8). This function should be reproduced on the basis of the recorded changes of body surface temperatures. Because of complex temperature histories, a sufficiently large number of terms of the trigonometric series (8) should be taken so as to maintain the required accuracy of mapping of the boundary condition. Of some help may be here the Fast Fourier Transform (FFT) procedures.

Calculating the integral by means of approximation methods can also solve equation (7). The derivative $\dfrac{dT}{d\tau}$ in the given time step can be approximated by the difference quotient $\dfrac{\Delta T_k}{\Delta \tau_k}$. This is a suitable approach, because in the state-of-the-art measuring devices experimental data are collected in the form of a series of discrete values. Thus, the integral in equation (7) can be presented in the form of a sum of integrals calculated for particular time steps. So, for the moment t_n we have:

$$q(t_n)=\sqrt{\frac{\lambda\rho c}{\pi}}\sum_{k=1}^{n}\frac{\Delta T_k}{\Delta\tau_k}\int_{t_{k-1}}^{t_k}\frac{1}{\sqrt{t_n-\tau}}d\tau . \tag{10}$$

The integral at the right hand side of equation (10) can be calculated analytically:

$$\int_{t_{k-1}}^{t_k}\frac{1}{\sqrt{t_n-\tau}}d\tau=-2\sqrt{t_n-\tau}\Big|_{t_{k-1}}^{t_k}=2\left(\sqrt{t_n-t_{k-1}}-\sqrt{t_n-t_k}\right). \tag{11}$$

Then the equation (10) takes the form:

$$q(t_n)=2\sqrt{\frac{\lambda\rho c}{\pi}}\sum_{k=1}^{n}\frac{\Delta T_k}{\Delta\tau_k}\left(\sqrt{t_n-t_{k-1}}-\sqrt{t_n-t_k}\right). \tag{12}$$

Usually, measurements are carried out at equal time intervals $\Delta\tau$, so the time at any moment k is equal to $t_k=k\cdot\Delta\tau$. Substituting this to equation (12) we finally have:

$$q(t_n)=2\sqrt{\frac{\lambda\rho c}{\pi\Delta\tau}}\sum_{k=1}^{n}(T_k-T_{k-1})\left(\sqrt{n-k+1}-\sqrt{n-k}\right). \tag{13}$$

Time interval $\Delta\tau$ should be small enough to ensure the required approximation accuracy. According to the Nanmac catalogue [4], this requirement is satisfied by the interval of the order of 1 millisecond. Relationship (13) provides a very suitable formula for computer calculations of the local heat flux on the basis of the measured changes of temperatures of the heat exchange surfaces.

3. Experimental stand

In the heat transfer investigations, the exact knowledge of experimental conditions is of great importance. The time needed to set up thermal conditions of the compressor is long, and after this time the conditions change because of periodic processes, which take place in the cylinder. These problems can be solved by constructing a special experimental set-up enabling single working cycles to be carried out.

For this purpose, the driving system of a mechanical eccentric press was used. A mechanical clutch starts the drive from the flywheel in a strictly determined place and disconnects it after one revolution is completed, and the brake stops the shaft. The driving system also makes it possible to adjust the piston stroke due to which the compression ratio can be changed.

During the cycle, a fast air compression and expansion take place, and the accompanying change of gas temperature causes an intensive heat transfer inside the cylinder. The initial experimental conditions were determined explicitly. The walls of the compression chamber and air in the cylinder had the same, steady temperature.

Fig. 1 shows a schematic diagram of the measuring equipment. The Nanmac E12-2 sensor was used for surface temperature measurements of the plate closing the cylinder. Inside the jacket of external diameter 4.7 mm, made from 304SS steel, there is an E-type chromel-constantan thermocouple of high thermoelectric power (6.317 mV/100°C). The thermocouple was installed in a fit hole in a such a manner that the junction was placed in the same plane as the inner surface of the plate. This plate was made from stainless steel (0H18N9), because its thermal properties were closest to those of the thermocouple materials [3].

The same thermocouple was used in the measurement of the piston head temperature. An original piston made from AK12 alloy was applied. The alloy consisted of aluminium, about 12% silicon, copper, magnesium and nickel (ca. 1% each). Thermal conductivity of this alloy is much lower than that of a pure aluminium and equals to about 130 W/mK. However, it is several times higher than that of steel. The sensor in the piston head causes a significant deviation of the temperature field in the body, which makes the measurements unreliable.

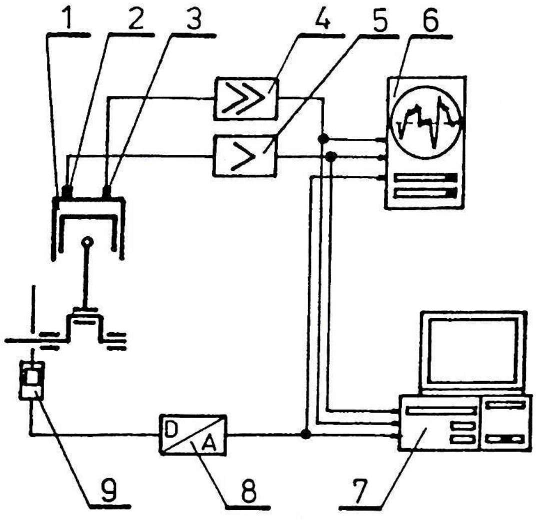

Fig. 1. Schematic diagram of measuring equipment; 1 – cylinder with a piston, 2 – pressure transducer, 3 – eroding thermocouple, 4 – low noise, hign gain amplifier, 5 – charge amplifier, 6 – oscilloscope, 7 – PC based data acquisition system, 8 – piston stroke transducer, 9 –photoelectric sensor

Therefore, an insulating layer 0.1 mm thick made from a capacitor tissue was used. Heat flux perpendicular to the thermocouple axis was reduced considerably, and the thermocouple showed correct, undisturbed temperature of the junction [3].

During the measurements, air pressure in the cylinder and piston displacement were also recorded. All data were collected by a PC-based acquisition system.

4. Results

Measurements by means of the eroding thermocouple were performed using the same air compression process in the cylinder. Figure 2 shows the pressure change during the single cycle. The compression ratio was chosen so that the obtained thermocouple signal was high enough in relation to the noise produced by the amplifier. Despite high thermocouple sensitivity, it was necessary to use a preamplifier with a gain of 10000 V/V and appropriately wide transfer band.

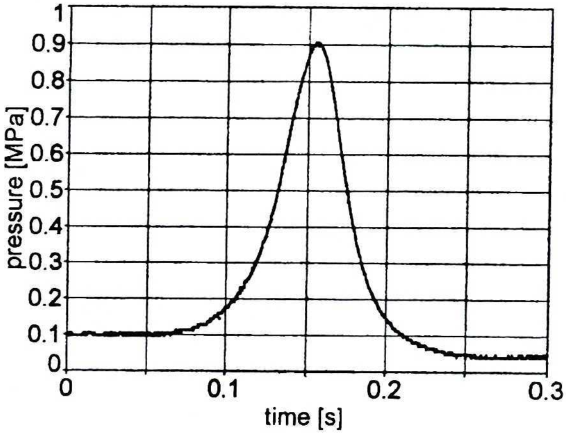

Fig. 2. Change of air pressure in the cylinder

Rapid change of air temperature followed the pressure and caused an intensive heat transfer to the cylinder walls. The thermocouple recorded an increment of instantaneous surface temperature equal to about 2 K (Fig. 3). The temperature signal was quite high, but noise disturbances were observed, particularly in the flat part of the diagram. This made it difficult to calculate the heat flux rate because temperature derivatives calculated from experimental data were burdened with serious errors. Either filtration or signal smoothing methods had to be used.

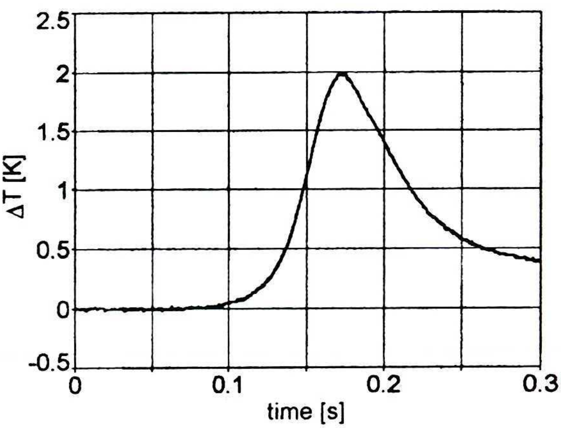

Fig. 3. Surface temperature record of the plate closing the cylinder

Figure 4 shows the Fourier domain analysis of the thermocouple signal. Using the Fast Fourier Transform (FFT) method, high frequency (above the 15th harmonic) components of the signal were removed. The temperature signal after removing the noise is displayed in Fig. 5. The noise was excluded, and the temperature time histories and the amplitude were not deformed.

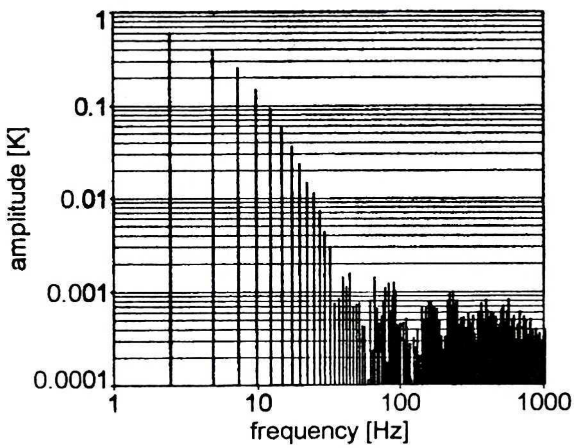

Fig. 4. Fourier spectrum of the thermocouple signal

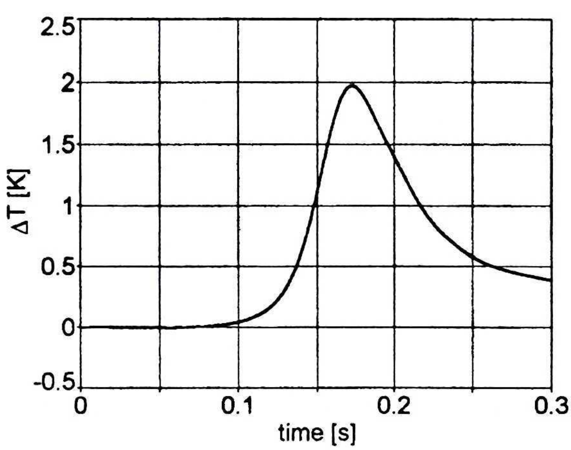

Fig. 5. The thermocouple signal after removing the noise

The obtained temperatures were used to calculate the local heat flux rate according to equation (13). Figure 6 shows results of the calculations. The heat flux increases rapidly and then decreases following changes in the gas pressure and temperature. Before the piston stops, the heat flux changes the direction due to air temperature drop, inside the cylinder, below the ambient temperature. After the piston stops, a slow return to thermal equilibrium is observed.

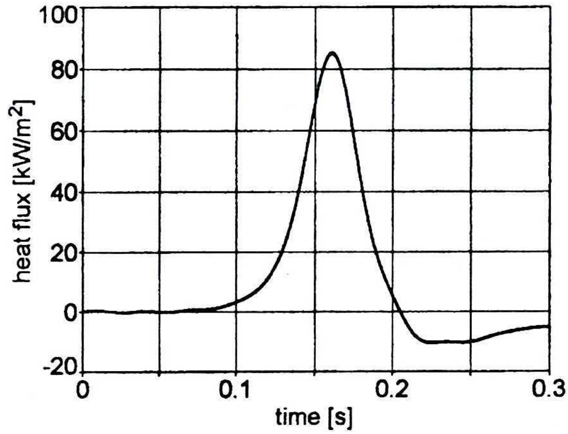

Fig. 6. Calculated heat flux rate to the plate closing the cylinder

Similar experiments were carried out to determine heat exchange on the piston head. Figure 7 shows changes in temperature revealed by the thermocouple built into the piston. Because of using the insulating layer, the thermocouple showed the temperature of its own head and not that of the piston surface. In this case, as the same compression cycle was used, the recorded temperature was close to that obtained for the plate closing the cylinder (Fig. 2). Only at the final stage of the process some slight differences were observed.

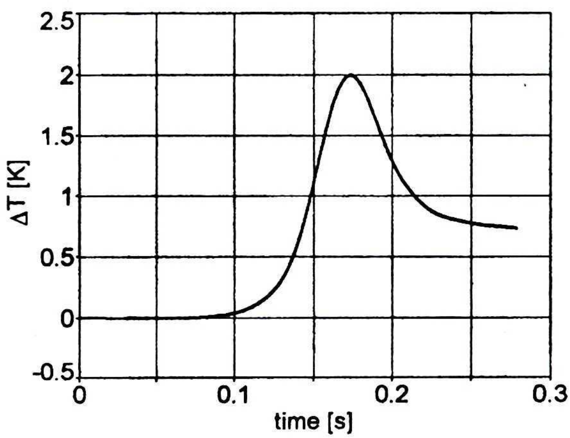

Fig. 7. Surface temperature of the piston crown

The temperature record, after noise removing, was used to calculate the local heat flux. In the calculations, one assumed thermal properties as for stainless steel since they well approximated the equivalent properties of the materials of which the sensor was made [3]. Results of calculations of the heat flux rate are shown in Fig. 8. Some differences are observed at the final stage. Once an intensive heat transfer due to compression and decompression cycle is completed, the temperatures in the thermocouple and piston start to equalise. Owing to much higher thermal conductivity and diffusivity of the material of which the piston is made, the penetration depth of the temperature wave is higher and becomes comparable to the piston head thickness. That is why the process of temperature equalisation is of a different kind.

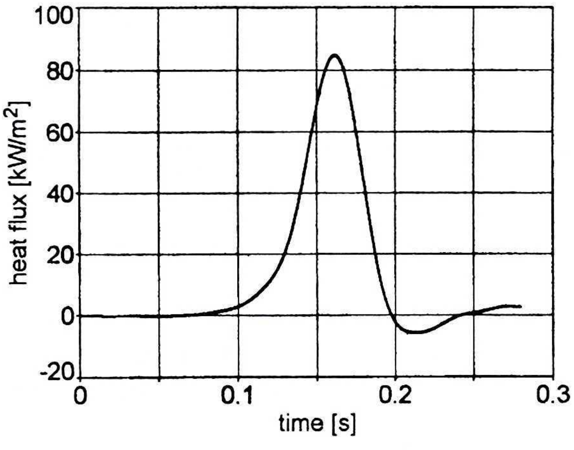

Fig. 8. Calculated heat flux rate to the piston head

5. Conclusions

The investigations confirmed suitability of the Nanmac eroding thermocouples in the measurement of unsteady temperature of a heat-exchanging surface. Used in the investigation of heat transfer in the cylinder, they appeared to be sensitive and fast enough. The measurements were carried out in an experimental set-up enabling single gas compression and expansion cycles. The results obtained confirmed high repeatability of the unsteady heat transfer process.

After noise removal, the changes of temperature were used to calculate heat flux rates on the inner surface of the plate closing the cylinder and of the piston head. Results of the calculations are almost the same in these two cases. Because of significant differences in thermal conductivity and diffusivity of the thermocouple and piston materials, it was necessary to apply an insulating layer which reduced heat transfer through the side surface of the thermocouple.

The method discused above can be applied also to measurements of temperature and heat flux determination in an engine cylinder with combustion.

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Eksperymentalne wyznaczanie nieustalonego strumienia cieplnego wewnątrz cylindra sprężarki przy użyciu termoelementów erozyjnych

Streszczenie

W pracy przedstawiono zastosowanie termoelementów erozyjnych do eksperymentalnego wyznaczania nieustalonego strumienia ciepła wymienianego wewnątrz cylindra sprężarki tłokowej. Jego konstrukcja i sposób wykonania złącza pomiarowego zapewnia bardzo małą bezwładność cieplną czujnika. Przy pomocy takiego termoelementu rejestrowano zmiany temperatury powierzchni wymieniającej ciepło.

Termoelement erozyjny wykorzystano do pomiaru chwilowej temperatury wewnętrznej powierzchni płyty zamykającej cylinder oraz powierzchni denka tłoka. Ze względu na niewielką amplitudę sygnału termoelektrycznego zastosowano wzmacniacz pomiarowy o bardzo dużym wzmocnieniu i odpowiednim paśmie przepustowym. Zarejestrowane dane eksperymentalne poddano numerycznej obróbce w celu usunięcia szumu wprowadzonego przez układ pomiarowy a następnie wykorzystano do obliczenia gęstości lokalnego strumienia ciepła. Dla zapewnienia powtarzalności pomiarów badania przeprowadzono na specjalnie zbudowanym stanowisku umożliwiającym realizację pojedynczych cykli sprężania.