UNSTEADY PERIODIC CONTACT HEAT-TRANSFER

G. B. Rozenblut and L. G. Gulyanskii UDC 536.24

This paper presents results of an investigation of unsteady periodic heat-transfer, carried out on a special experimental facility.

The need for study of contact heat-transfer has been evidenced in recent years by a considerable increase in the heat losses at joints between elements of power equipment. Most known papers [1-3 etc.] on contact heat-transfer deal with the case of constant resistance of the surfaces in contact and steady-state heat-transfer conditions between them. From this work the main laws of steady-state contact heat transfer have been developed. The theoretical and experimental data have been used to derive relationships for determining the contact heat-transfer coefficient α_{ch} for steady-state contact heat-transfer.

In a number of power equipment (piston-type internal combustion engines, compressors, etc.) one sees unsteady periodic contact heat-transfer between heat-loaded members such as values and cylinder heads, compression rings, and pistons. To a considerable degree it determines the thermal conditions of these members v and in many cases it determines the system efficiency as a whole. However, the laws for this process have not yet been studied, and attempts to apply known theoretical relations for steady-state contact heat-transfer [1-3 etc.] to unsteady periodic contact heat-transfer leads to considerable errors. In most cases calculated values exceed the experimental values by an order of magnitude and more.

Therefore, unsteady periodic contact heat-transfer was investigated on a special laboratory facility. With this facility one could establish the individual influence on unsteady periodic contact heat transfer of a number of governing parameters: contact pressure, contact cycle frequency, the duty factor, etc. Periodic contact and loading of the contact surfaces of test specimens were accomplished using an electric motor, a reducing gear, and an eccentric roller. The required heat flux through the contact region was achieved with an electrical heater and a water cooler in which the test specimens were located.

This method of investigation is based on recording the temperature fluctuations at the contact surfaces. Subsequent reduction of these oscillations makes it possible to obtain instantaneous values of the specific heat flux.

Two methods of determining the specific heat flux were used. The first is based on the fact that the process of varying the wall temperature with time can be represented as the result of applying periodic temperature fluctuations to a steady temperature field. With sufficient accuracy, the temperature field at the contact zone can be considered as one-dimensional, i.e., as dependent only on the single coordinate x in the direction perpendicular to the contact surface. Then the differential equation of heat conduction has the form

$$\frac{\partial t}{\partial \tau} = a\frac{\partial^2 t}{\partial x^2}. \tag{1}$$

As is known from the mathematical theory of heat conduction, the integral of this equation can be represented by the relation

$$t = t_{st} - \frac{q_{st}}{\lambda}x + \sum_{k=1}^{\infty}\left[\exp\left(-x\sqrt{\frac{k\omega}{2a}}\right)\right]\left[A_c\cos\left(k\omega\tau - x\sqrt{\frac{k\omega}{2a}}\right) + B_c\sin\left(k\omega\tau - x\sqrt{\frac{k\omega}{2a}}\right)\right]. \tag{2}$$

For the case of temperature oscillations at a surface, Eq. (2) takes the form

$$t = t_{st} + \sum_{k=1}^{\infty}(A_c\cos k\omega\tau + B_c\sin k\omega\tau). \tag{3}$$

The specific heat flux is determined by differentiating Eq. (2), and at x = 0 it has the form

---

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 37, No. 5, pp. 898-904, November, 1979. Original article submitted October 10, 1978.

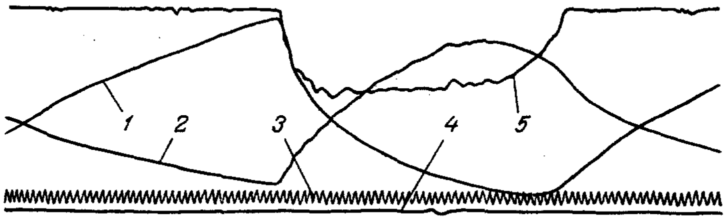

Fig. 1. Oscillograms of temperature oscillations for two adjacent points on the contact surfaces of test specimens with $f_{cyc} = 7.2$ Hz, $\tau_c/\tau_{cy} = 0.46$: 1) temperature of specimen in the heater and 2) in the cooler; 3) time marks; 4) rotational frequency marks; 5) contact pressure; the scale for temperature is $0.64 \cdot 10^3$ °C/m and for pressure, $3.5 \cdot 10^3$ MPa/m.

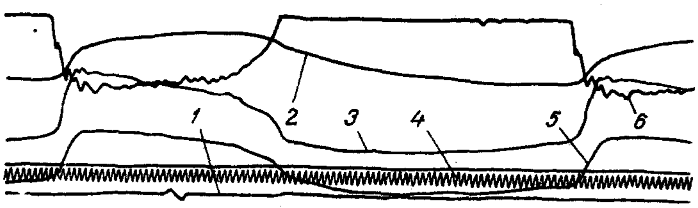

Fig. 2. Oscillograms of temperature oscillations for the surface contact point of a specimen in the cooler, and the specific heat flux at two values of distance from the contact surface, obtained using an RC circuit with $f_{cyc} = 7.2$ Hz, $\tau_c/\tau_{cy} = 0.43$: 1) rotational frequency marks; 2) surface temperature; 3) heat flux at depth $0.1 \cdot 10^{-3}$ m; 4) time marks; 5) heat flux at depth $0.2 \cdot 10^{-3}$ m; 6) contact pressure; the scale of temperature is $1.6 \cdot 10^3$ °C/m, and of pressure $3.7 \cdot 10^3$ MPa/m; the flux at the lower depth is $71.8 \cdot 10^6$ W/m^3 and at the higher depth, $92.6 \cdot 10^6$ W/m^3.

$$q = -\lambda \frac{\partial t}{\partial x} = q_{st} + \lambda \sum_{k=1}^{\infty} \sqrt{\frac{k\omega}{2a}} \left[(A_c + B_c)\cos k\omega\tau + (B_c - A_c)\sin k\omega\tau\right]. \quad (4)$$

The instantaneous values of specific heat flux were also determined by the electrothermal analogy method. In this method the emf from a surface thermocouple is amplified electronically and applied to a modeling RC circuit, consisting of resistors and capacitors. With this method one can directly record periodic varying heat flux at the wall. Here the thermal resistance in surface contact is modeled by ohmic resistance, the heat capacity is modeled by electrical capacitors, the temperature in the real situation is modeled by voltages in the model, and the heat flux is modeled by the current. To retain the proportion at corresponding points between the model and the real situation one must equalize the scales of temperature, heat capacity, thermal resistance, heat flux, and time. Then a given depth in the wall from the surface in the real situation corresponds to a definite section in the RC circuit analogy, and the measured current there, allowing for the scale, gives a direct value of the heat flux. Then q is expressed in terms of the characteristics of the measuring system by the relation

$$q = \lambda r y_q / \mu k_a c_s. \quad (5)$$

From a simultaneous record of the current at two small distances from the model surface (x_1 and x_2) one can use the equations $q = q_{x_1}[\exp(x_1\gamma)]$, $q = q_{x_2}[\exp(x_2\gamma)]$ to determine γ and the specific heat flux at the contact surface.

The temperature oscillations and the heat fluxes are recorded using thermocouples, an electronic amplifier, and a loop oscillograph. The calculations of Eqs. (2) and (3) were performed using a computer program.

The area of the actual contact, which plays a considerable part in determining α_{ch}, was investigated experimentally by the surface film method, using the radioactive isotope ^{63}Ni and a special device. One of the contact surfaces was covered electrolytically by a thin layer of radioactive isotope. The area of actual contact was determined from the intensity of emission of the isotope transferred to the other surface after contact. The distribution of isotope at the places of actual contact was determined by a photometric method.

Before the experiments on unsteady periodic contact heat transfer were begun, the operation of the laboratory facility and the measuring equipment was checked under continuous conditions of constant contact of the surfaces under load and with steady-state heat-transfer conditions. A comparison of the results obtained with the data given in [1-3] shows satisfactory agreement. This is evidence that the facility and the measuring system are capable of obtaining reliable data.

By way of example, Fig. 1 shows oscillograms of temperature oscillations at two points of the contact surfaces, and Fig. 2 shows oscillograms of temperature oscillations and heat flux. It can be seen that, from the moment of contact of the surfaces, as the contact pressure increases, there is a lowering of the temperature of a specimen mounted in the heater, and an increase in temperature for a specimen set up in the cooler. The greatest values of specific heat flux correspond to the greatest contact pressures.

The results of these experimental investigations were analyzed using similarity variables.

The contact heat-transfer coefficient depends on a number of interrelated characteristics and can be represented in the form

$$\alpha_{ch} = f(P_s, \sigma_t, \tau_c, \tau_{cy} f_{cy} \lambda_m, \lambda_{re}, \delta_{eq}),$$

where $\lambda_{re} = f(\lambda_1, \lambda_2, h_1, h_2)$; $\delta_{eq} = (h_1, h_2, P_c, \sigma_t, \eta, \psi)$. The thermal conductivity of the materials of the contact pair was determined, both for a multilayer wall and when a thermally insulating film was present at the contact surface:

$$\lambda_{re} = (h_1 + h_2 + h_f) \Big/ \left(\frac{h_1}{\lambda_1} + \frac{h_2}{\lambda_2} + \frac{h_f}{\lambda_f}\right). \tag{6}$$

The quantities h_1, h_2, h_f were determined from the oscillograms taken with the contact surfaces. For pure surfaces the quantities h_f, λ_f do not appear in Eq. (6).

The equivalent thickness of the intercontact gap $\delta_{eq} = \delta - l$. We took δ to be the sum of the heights of profile irregularities [3], determined after the surfaces were machined. Allowing for the relative separation $\varepsilon = l/\delta$ we obtain

$$\delta_{eq} = (h_1 + h_2)(1 - \varepsilon). \tag{7}$$

The relative separation ε is linked to the relative area of actual contact η by the relation $\varepsilon = (\eta/b)^{1/\nu}$. Then the expression to determine the equivalent thickness of the intercontact gap takes the form

$$\delta_{eq} = (h_1 + h_2)\left[1 - \left(\frac{\eta}{b}\right)^{1/\nu}\right]. \tag{8}$$

From dimensional analysis, the governing heat-transfer equation can be represented in the form

$$Nu_{ch} = f_1\left(\frac{\lambda_m}{\lambda_{re}}\right) f_2\left(\frac{P_c}{\sigma_t}\right) f_3\left(\frac{\tau_c}{\tau_{cy}}\right) f_4\left(\frac{f_{cy}}{f_0}\right). \tag{9}$$

From the experimental investigations we determined the influence of variation of P_c, τ_c, f_{cy} on the intensity of unsteady periodic contact heat transfer. Here we determined the individual influence of the above parameters on the heat-transfer. Some of the results of the experimental investigations are shown in Figs. 3 and 4. Here $\overline{Nu}_{ch}$ and $\overline{P}_c$ were determined by averaging and time-integration over the contact time of the instantaneous values of Nu_{ch}

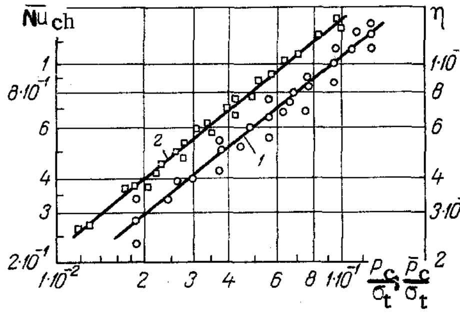

Fig. 3

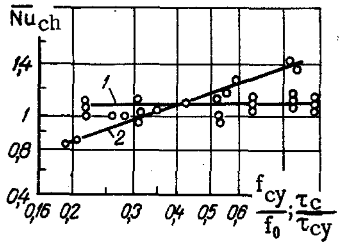

Fig. 4

Fig. 3. The value of $\overline{Nu}_{ch}$ averaged over the contact time as a function of $\overline{P}_c/\sigma_t$ (1) and of the actual relative contact area η as a function of P_c/σ_t (2).

Fig. 4. The quantity $\overline{Nu}_{ch}$ averaged over the contact time as a function of τ_c/τ_{cy} (2) and of f_{cy}/f_0 (1).

and P_c. From the figures we can see that with increase of contact pressure and the porosity of contact there is an increase in $\overline{Nu}_{ch}$. The increase of $\overline{Nu}_{ch}$ with increase of contact pressure is due mainly to an increase in η because of an increase of the number and area of the apices of irregularities protruding into the contact. It is known that the contact area is formed most vigorously in the initial period of contact, and therefore an increase in porosity also favors an increase of η and $\overline{Nu}_{ch}$.

An increase of f_{cy} in the investigated range, corresponding to 2.5-12 Hz, as is shown in Fig. 4, has no appreciable influence on $\overline{Nu}_{ch}$. The analysis made showed that, with increase in frequency, in the range of frequency investigated the influence of increase of P_c on η is compensated by a reduction in η due to a reduced time of contact. For this reason $\overline{Nu}_{ch}$ remained practically unchanged, and the quantity f_{cy}/f_0 can be omitted in Eq. (9).

It was established experimentally that α_{ch} is roughly an order of magnitude lower for unsteady periodic contact heat transfer than for steady-state contact heat-transfer. The probable reason is that the formation of the area of actual contact in unsteady periodic contact occurs under dynamic loading conditions which differ appreciably from the steady-state loading.

From the processing of the test data, Eq. (9) takes the form

$$\overline{Nu}_{ch}=c\left(\frac{\overline{P}_c}{\sigma_t}\right)^{0.8}\left(\frac{\tau_c}{\tau_{cy}}\right)^{0.3} \tag{10}$$

to determine the value averaged over the contact time, where $c = 9200\,\lambda_m/\lambda_{re} - 78.7$ for contact surfaces with a thermally insulating film (carbon deposit, organic adhesive, etc.), $c = 17{,}100\lambda_m/\lambda_{re} - 6.1$ for clean contact surfaces, and for instantaneous values, with a thermally insulating film at the contact surfaces

$$Nu_{ch}=\left(1830\,\frac{\lambda_m}{\lambda_{re}}-15.6\right)\left(\frac{P_c}{\sigma_t}\right)^{0.43}. \tag{11}$$

The investigations of the actual contact area using radioactive isotopes established the dependence of η on the ratio P_c/σ_t, and this can be approximated satisfactorily by the equation

$$\eta=0.66\,(P_c/\sigma_t)^{0.8}. \tag{12}$$

The coefficients b and ν in Eq. (8) were obtained by constructing a curve for the support surface from the profilograms with contact surfaces and gave the values b = 10 and ν = 2.5. When these values are substituted in Eq. (8) we find

$$\delta_{eq}=(h_1+h_2)\left(1-0.34\sqrt[3]{\frac{P_c}{\sigma_t}}\right). \tag{13}$$

Taking account of Eq. (13), the Nusselt number for contact heat transfer may be represented in the form

$$\mathrm{Nu}_{ch} = (h_1 + h_2)\left(1 - 0.34\sqrt[3]{\frac{P_c}{\sigma_t}}\right)\frac{\alpha_{ch}}{\lambda_m}. \tag{14}$$

After transformation the calculated relations to determine the contact heat-transfer coefficient will have the following form: Corresponding to Eq. (10) we have

$$\bar{\alpha}_{ch} = \frac{c\left(\frac{\bar{P}_c}{\sigma_t}\right)^{0.8}\left(\frac{\tau_c}{\tau_{cy}}\right)^{0.3}\lambda_m}{(h_1 + h_2)\left(1 - 0.34\sqrt[3]{\frac{\bar{P}_c}{\sigma_t}}\right)} \tag{15}$$

and corresponding to Eq. (11) we have

$$\alpha_{ch} = \frac{\left(1830\,\frac{\lambda_m}{\lambda_{re}} - 15.6\right)\left(\frac{P_c}{\sigma_t}\right)^{0.43}\lambda_m}{(h_1 + h_2)\left(1 - 0.34\sqrt[3]{\frac{P_c}{\sigma_t}}\right)}. \tag{16}$$

The parametric relations obtained may be used to determine the instantaneous value, and the value averaged over the contact time, of the heat-transfer coefficient for unsteady periodic contact heat-transfer within the following measured range of the arguments: P_c/σ_t and $\bar{P}_c/\sigma_t \leqslant 1.4 \cdot 10^{-2}$; $\tau_c/\tau_{cy} = 1.6 \cdot 10^{-1}$–$8 \cdot 10^{-1}$; $\lambda_m/\lambda_{re} = 1 \cdot 10^{-3}$–$1.6 \cdot 10^{-3}$ for clean contact surfaces, $\lambda_m/\lambda_{re} = 9 \cdot 10^{-3}$–$1.1 \cdot 10^{-2}$ for contact surfaces with a thermally insulating layer, in the range of contact frequencies f_{cy} = 2-12 Hz.

Calculations made using Eqs. (15) and (16) indicate that the divergence from the experimental data is less than 15%.

NOTATION

α_{ch}, contact heat-transfer coefficient; q, q_{st}, specific and steady heat flux through the contact zone; P_c, contact pressure; λ, λ_f, λ_m, thermal conductivities of the materials of the contact pair, the thermally insulating film, and the intercontact medium; λ_{re}, reduced thermal conductivity; σ_t, strength limit of the material; h_1, h_2, heights of contact-surface profile irregularities; h_f, thickness of the thermally insulating film; η, relative area of actual contact; ψ, contraction coefficient; τ_c/τ_{cy}, duty factor (ratio of contact duration to working cycle duration); f_{cy}/f_0, relative frequency (ratio of contact cycle frequency to a fixed frequency); a, thermal diffusivity; t_{st}, steady temperature at depth x from the contact surface; k, order of harmonic; ω, cyclic frequency; A_c, B_c, Fourier series coefficients; k_a, amplifier gain; y_q, heat-flux coordinate on the oscillogram; c_s, constant stub; l, absolute distance of separation; δ, intercontact gap at zero load; b, ν, coefficients describing the surface roughness; ε, relative separation of surfaces; μ, thermocouple sensitivity; r, specific electrical resistance.

LITERATURE CITED

1. Yu. P. Shlykov, Teploenergetika, No. 10 (1965).
2. V. M. Popov, Heat-Transfer in the Contact Region for Detachable and Nondetachable Joints [in Russian], Énergiya, Moscow (1971).
3. V. S. Miller, Contact Heat-Transfer in Elements of High-Temperature Machinery [in Russian], Naukova Dumka, Kiev (1966).