

METHOD FOR MEASUREMENT OF LOCAL THERMAL CURRENTS

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A new method is presented for measurement of local thermal currents on the boundary surface between a solid and a gas or liquid. The principles of measurement are explained, construction of the device is described, and results of experimental testing are offered.

In practical thermophysical studies it is often necessary to determine the local convective thermal-current field on the boundary surface between a solid and the surrounding medium. Measurements of this type are hindered by significant technological difficulties which become more intense as temperature inhomogeneity within the working zone increases.

At the present time, measurement of such currents is usually achieved by stationary calorimeters: those with a conductive wall and electrical compensation of the thermal current, and enthalpy flow devices [1]. The most versatile from the viewpoint of sensitivity, working temperature range, and low inertia are the conductive wall calorimeters. Unfortunately, the construction technology for such calorimeters is quite complex and cannot guarantee reproducibility of thermal characteristics in individual instruments, thus requiring calibration of each instrument under conditions close to those of the intended use. Their use is justified in large scale measurements of a technological nature. However, for performance of a series of scientific studies, calorimeters operating upon other physical principles may prove more suitable. In particular, for measurement of local thermal currents on the boundary between a nonisothermal gaseous medium and bodies of arbitrary form it is convenient to use nonstationary metallic calorimeters, as were first described briefly in [2].

We recall that in the case considered (Fig. 1), a thin metallic plate (calorimeter) 1 is placed in the direct vicinity of the portion of the object surface to be studied 3, remaining separated from the surface by a thin gas layer 2. The dimensions and form of the plate are chosen such that as far as possible it will not introduce distortions into the hydrodynamic boundary layer of the surrounding medium, and such that the portion of the object surface covered may be considered local and isothermal. The emissivity of the plate ϵ_T must equal that of the surface area studied ϵ_S ($\epsilon_S = \epsilon_T$).

It will be convenient to analyze the operation of the calorimeter with the aid of Fig. 2. We will consider the case where the surface studied is heated higher than the medium ($t_S > t_{me}$). In the steady state the plate temperature t_T must satisfy the condition $t_{me} < t_{T,\infty} < t_S$, and so before the experiment the plate is heated somewhat relative to the surface area ($t_{T,0} > t_S$). Then the plate ($t_{T,0} > t_S$) cools freely along the curve $t_T(\tau)$ and at moment τ_0 , when $t_T = t_S$, its cooling is totally determined by heat exchange with the medium.

If we neglect the heat capacity of gas interlayer 2 (Fig. 1), the fundamental equation for the flux q at $t_T = t_S$ will have the form

$$q = -\frac{C_\tau}{F_\tau} b_\tau^0, \quad |b_\tau^0 < 0|, \quad (1)$$

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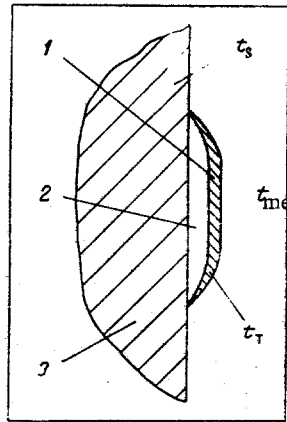


Fig. 1. Thermal model of measurement device.

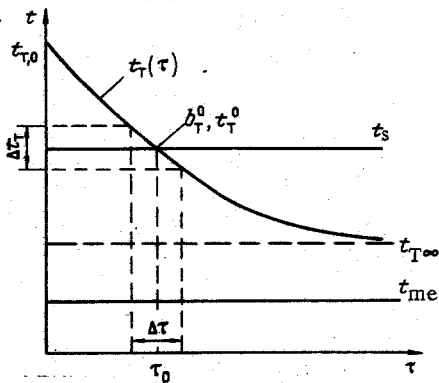


Fig. 2. Method of thermal-current measurement.

where C_T and F_T are the total heat capacity and area of the heat-liberating surface of the plate; the flux is assumed positive when $t_s > t_{me}$.

The direction of the flux q is determined by the sign of the rate of change of plate temperature b_T^0 . In accordance with Eq. (1) at $b_T^0 < 0$ the flux q is directed into the medium and, conversely, at $b_T^0 > 0$ it goes from the medium. Figure 2 corresponds to the case $b_T^0 < 0$. The second case ($b_T^0 > 0$) indicates that $t_s < t_{me}$, and so the calorimeter must be cooled before the measurement so that $t_{T,0} < t_s$.

The calorimeter indications are independent of thickness and thermal conductivity of the gas layer and depend solely on the parameters C_T and F_T of the plate. The plate form and dimensions are arbitrary in principle.

Consequently, a calorimeter of this type may be constructed as a universal transfer-measurement device for convective, conductive, and radiant thermal flux, not requiring individual calibration. With sufficient miniaturization the calorimeter need not introduce detectable hydrodynamic or thermal resistance into the boundary layer. Aside from the small dimensions and shape of the calorimeter, the brevity of the time period over which it remains near the area studied and the fact that there is only a small temperature difference between plate and surface (the temperatures coincide at the time of measurement) tend to eliminate distortion of the experimental conditions.

Errors produced by the presence of the calorimeter as a foreign body may be completely eliminated if the plate can be directly built into the area of interest, without disturbing its surface contours. Such situations often occur in laboratory studies.

It is advantageous to construct built-in calorimeters in a manner such that the medium to be studied cannot penetrate into the insulation-layer cavity. Hermetization of the calorimeter is especially important when it is intended for use with liquid or aggressive media. It is thus appropriate to generalize Eq. (1) to the case of an arbitrary thermally insulating layer possessing significant thermal capacity. For simplicity, we will assume that the interlayer is nominally planar and is in ideal thermal contact with the calorimeter plate and ring. An equivalent thermal model of such a calorimeter is shown in Fig. 3. Being preheated before the experiment relative to the surface ($t_{T,0} > t_s$), the metallic calorimeter plate T , together with the insulating layer I cool freely in the nonisothermal medium with temperatures t_s and t_{me} , tending to a stable state (dot-dashed line). According to the generalized theory of a regular thermal regime [3], in such a system, long before the stationary state there is established a cooling regime, in which all its layers change their temperature differential $\vartheta(x, \tau) = t(x, \tau) - t(x, \infty)$ by an exponential law with a rate m common to the entire system.

Consequently, in the so-called regular stage of cooling the temperatures of plate T and insulating layer I must obey the laws

$$t_T(\tau) = t_T(\infty) + Ae^{-m\tau}; \quad t_I(x, \tau) = t(x, \infty) + B \sin(\nu x - \varphi) e^{-m\tau}, \quad (2)$$

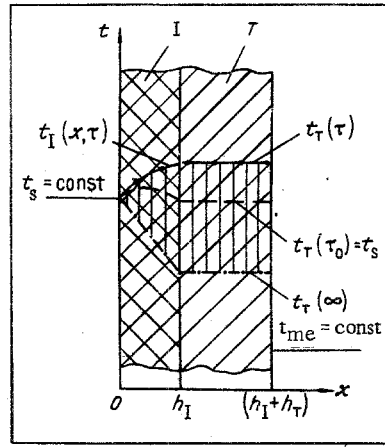


Fig. 3. Equivalent thermal model of calorimeter.

where $\nu^2 = m/a_I$; a_I is the thermal diffusivity of the insulation layer.

To complement Eq. (2) we use the problem boundary conditions

$$t_I(0, \tau) = t(0, \infty) = t_s; \quad t_I(h_I, \tau) = t_T(\tau);$$

$$\lambda_I \frac{dt_I}{dx} \Big|_{x=h_I} = -c_T \rho_T h_T \frac{dt_T}{d\tau} - \alpha(t_T - t_{me}), \quad (3)$$

where α is the heat-transfer coefficient between plate T and the medium; $c_T \rho_T$ is the volume heat capacity of the calorimeter plate; λ_I is the thermal-conductivity coefficient of insulating layer.

With appropriate substitution in Eqs. (2), (3) we obtain

$$t_T(\tau) = t_T(\infty) + Ae^{-m\tau};$$

$$t_I(x, \tau) = t_s - [t_s - t_T(\infty)] \frac{x}{h_I} + A \frac{\sin \nu x}{\sin p} e^{-m\tau}, \quad (4)$$

where

$$p = \nu h_I; \quad \frac{p}{\operatorname{tg} p} = (c_T \rho_T h_T m - \alpha) \frac{h_I}{\lambda_I}; \quad t_s - t_T(\infty) = \frac{\alpha h_I}{\lambda_I} [t_T(\infty) - t_{me}].$$

If the calorimeter parameters satisfy the important physical requirement

$$C_I \leq 0.3 C_T, \quad (5)$$

the relationships of Eq. (4) may be simplified. In particular, the expression for system cooling rate, with an error $\delta_m \leq 0.01$, may be written as

$$m = \frac{\left(\frac{\lambda_I}{h_I} + \alpha \right) F_T}{C_T + \frac{1}{3} C_I}. \quad (6)$$

Here C_T and C_I are the total heat capacities of the plate and the insulating layer.

From Eqs. (4), (6) after appropriate transformations we obtain the final working formula for calculation of the thermal flux of interest $q = \alpha(t_s - t_{me})$, namely:

$$q = - \frac{\left(C_T + \frac{1}{3} C_I \right)}{F_T} b_T^0, \quad |b_T^0| < 0. \quad (7)$$

This generalized formula differs from the initial one, Eq. (1), only in a correction for the heat capacity of the insulating layer. Consequently, the presence of a thermally insulating interlayer whose heat capacity satisfies the limitations of Eq. (5) does not complicate use of the calorimeter or reduce its metrological capabilities by any practical amount. However, use of quite reliable data on heat capacity of not only the metallic plate, but also the insulating layer, is then necessary. Thus, in calorimeter design it is expedient to utilize interlayers with the minimum possible heat capacity.

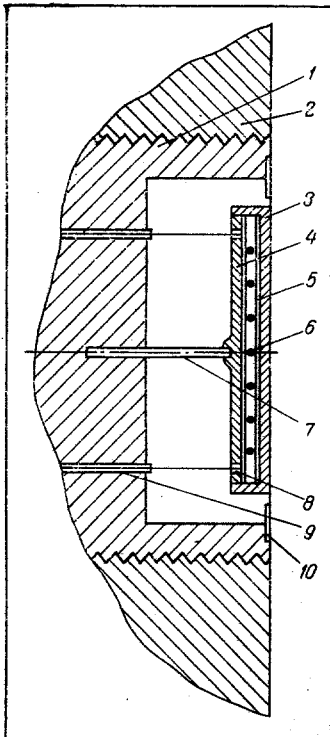


Fig. 4. View of measurement apparatus.

In particular, if the limitation

$$C_I \leq 0.03 C_T, \quad (8)$$

is satisfied, then in practice we may neglect the heat capacity of the interlayer and replace Eq. (7) with an error $\delta_m \leq 0.01$ by Eq. (1).

The metrologic capabilities of the calorimeter, unfortunately, do not depend only on the accuracy with which the parameters C_T , C_I , F_T are known. No less significant is the effect of the relationship between thermal conductivity of the insulating layer λ_I/h_I and the heat-exchange coefficient of the medium α . To verify this, we turn again to the calorimeter model of Fig. 1. We will use the concept of heat-exchange coefficient and write the desired thermal flux in terms of the temperature difference between surface and medium:

$$q = \alpha (t_s - t_{me}). \quad (9)$$

Further, we assume that the calorimeter-plate cooling rate is measured not exactly at the moment when $t_T(\tau_0) = t_s$, but with a temperature difference Δt . This error Δt , in the general case, is composed of systemic error in plate and surface thermocouple indications and instrument error in the measurement circuits. But at a temperature level $t_T = t_s + \Delta t$ the calorimeter already records a flux

$$q + \Delta q = \alpha (t_s + \Delta t - t_{me}) + \frac{\lambda_I}{h_I} \Delta t. \quad (10)$$

Consequently, in measuring the flux q there occurs a relative error $\delta_q = \Delta q/q$:

$$\delta_q = \left(1 + \frac{\lambda_I}{\alpha h_I} \right) \cdot \frac{\Delta t}{t_s - t_{me}}. \quad (11)$$

Equation (11) may be used in calorimeter design to reconcile admissible values of δ_q , Δt and h_I/λ_I . In particular, if the expected values of α_{\min} , $(t_s - t_{me})_{\min}$, Δt_{\max} are known and the admissible relative error in thermal-flux measurement δ_q is given, then the parameters of the thermally insulating interlayer must satisfy the limitation

$$\frac{\lambda_I}{h_I} \leq \alpha_{\min} \left[\frac{(t_s - t_{me})_{\min} \delta_q}{\Delta t_{\max}} - 1 \right]. \quad (12)$$

Since the calorimeter cooling rate b_T is determined not at a point, but within a temperature range Δt_T and time range $\Delta \tau$, incorrect selection of these intervals may lead to significant measurement errors.

It can be shown that the relative error in cooling-rate measurement δ_T is equal to

$$\delta_T = \frac{\Delta b_T}{b_T^0} = \frac{1}{24} (m \Delta \tau)^2 \quad \text{or} \quad \delta_T = \frac{1}{24} \left(\frac{\Delta t_T}{t_r^0 - t_{r,\infty}} \right). \quad (13)$$

Equation (13) permits selection of optimal experimental conditions at which δ_T will be minimum.

The metallic calorimeter considered above was used for measurement of local heat-transfer coefficients in air interlayers at various barometric pressures.

Measurements were made of the coefficient of heat transfer between two isothermal brass plates ($200 \times 200 \times 15$) mm, with temperatures stabilized by flowing water to an accuracy of $\pm 0.1^\circ$. The end surfaces of the gaseous interlayer between the plates were enclosed along the perimeter by four brass covers mounted to the plates by Teflon thermal-insulating spacers. All internal surfaces of the interlayer were given a polished chromium finish to reduce the radiant component of the thermal flux.

A general view of the measurement apparatus is shown in Fig. 4. The calorimeter is located in a cylindrical depression 17 mm in diameter and 4 mm deep, formed in copper ring 1, which, in turn, is mounted in heater plate 2 with a threaded coupling.

The calorimeter plate consists of two copper disks 3, 4, 15 mm in diameter and 0.5 mm thick. Between them is placed a Nichrome-Constantan thermocouple 5, which is also used as a heater. The

thermocouple electrodes are formed of wires 0.1 mm in diameter shaped into a bifilar spiral. Layers of tissue paper 5 serve to electrically insulate spiral 6 from disks 3, 4. Individual parts of the calorimeter (3, 4, 5, 6) were mounted with epoxy resin. In assembling the sensor special attention was paid to ensuring a reliable mechanical contact between the thermocouple and disks 3, 4. The thermocouple-heater leads are brought out through porcelain insulator tubes 8, 9, 1 mm in diameter. The calorimeter is mounted to plate 1 with hard rubber dowel pin 7, 1 mm in diameter. Guard ring 10, made of copper foil 0.1 mm thick, serves to limit the heat-exchange area. The rate of change of calorimeter temperature is measured by a differential thermocouple with one junction in the calorimeter and the other thermally stabilized in a Dewar flask. Auxilliary equipment used consisted of a PPTN-1 potentiometer with an M 195/1 galvanometer. Time was measured with a stopwatch with 0.1-sec divisions.

Basic characteristics of the calorimeter were as follows: total heat capacity of calorimeter, 0.67 J/deg K; heat-liberation surface area, $1.83 \cdot 10^{-4} \text{ m}^2$; the specific thermal flux at which the calorimeter tests were performed varied over the range 10-500 W/m².

Control experiments were performed in the absence of convection, in which the thermal flux q transferred between plate and interlayer was determined from the formula

$$q = \frac{\lambda}{\delta} \Delta t_s + \varepsilon_{\text{in}} \cdot 5.67 \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right], \quad (14)$$

where λ is the thermal conductivity of air, W/m · deg K; δ is the interlayer thickness, m; T_1 , T_2 are the temperatures of plates bounded by the interlayer, °K.

The corrected emissivity coefficient of the interlayer $\varepsilon_{\text{in}} = 0.045$ was determined from separate experiments at a pressure of $P = 1 \cdot 10^{-4}$ torr, in which the thermal conductivity of the air could be neglected. Since the radiant component of the thermal flux does not exceed 20% of q , the temperature drop Δt_s was measured directly, and the thermal conductivity of the air was known to an accuracy of 1% [4]; Eq. (14) allows calculation of q with an error no more than 2%. Experiments were performed over a wide range of conditions: $\Delta t_s = 15$ -65 deg; air pressure 10, 100, 760 torrs; layer thickness 5, 10, 15, 20 mm; layer orientation vertical and horizontal (with upper and lower heated surface). Deviations in calorimeter indications calculated with Eq. (7) and results from Eq. (14) did not exceed 2.5%. This error was obtained in the steady-state regime.

In conclusion, it should be noted that the proposed method of thermal-flux measurement is applicable to measurements in both gaseous and liquid media, with various conditions of flow over the surface. Limitations on the measurement temperature range and thermal-flux range are determined basically by physical peculiarities of the actual calorimeter chosen. This method allows measurement of unstable thermal fluxes. However, such application will require further investigation.

NOTATION

ε	is the surface emissivity;
t	is the temperature, °K;
τ	is the time, sec;
b_T^0	is the cooling rate, deg K/sec;
q	is the specific heat flux, W/m ² ;
C	is the volumetric heat capacity, J/°K;
F	is the area of heat-liberating surface, m ² ;
m	is the cooling rate, sec ⁻¹ ;
a	is the thermal diffusivity, m ² /sec;
λ	is the thermal conductivity, W/m · deg K;
α	is the calorimeter — medium heat-exchange coefficient, W/m ² · deg K;
h	is the thickness, m;
A, B	are the oscillation amplitudes of mean volumetric temperatures of calorimeter and insulating layer;
c	is the specific heat capacity, J/kg · deg K;
ρ	is the density, kg/m ³ ;
δ_q	is the relative error in thermal-flux measurement;
P	is the medium pressure, mm Hg.

Indices

- s is the surface studied;
me is the medium;
 τ is the calorimeter plate;
I is the insulating interlayer.

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