MEASUREMENT OF TRANSIENT HEAT FLUX USING HEAT GAUGES

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This paper describes the theoretical basis, the design, and the method of calibrating heat gauges for measuring variable heat fluxes.

Auxiliary Wall Type of Heat Gauge*

Heat gauges based on the so-called auxiliary wall technique are widely used to measure heat flux. These gauges take the form of a thermal insulator carrying a differential thermocouple or thermopile. Recently, semiconductor heat gauges have found increasing use. For a steady flux $P$ the relation between the flux and the potential difference $\Delta E$ or temperature difference $\Delta t_m$ on the surface of a heat gauge is given by the well-known formula [1]

$$P = g\Delta E = k\Delta t_m.$$  

(1)

We consider the possible measurement of an unsteady heat flux using this type of gauge. We represent the gauge in the form of an infinite flat plate, one surface of which absorbs a heat flux $P(\tau)$, while the second surface exchanges heat with surrounding space in a different manner, i.e., there are several possible conditions at the boundary $x = l$ (Fig. 1a). Assuming that the thermophysical properties of the heat gauge and the heat-transfer conditions at the boundaries are independent of temperature, we can write a differential equation for the temperature field in the plate:

$$\lambda \frac{\partial^2 t}{\partial x^2} = \rho c \frac{\partial t}{\partial \tau}.$$  

(2)

We now apply the operator

$$I[f] = \frac{1}{l} \int_0^l fdx$$

(3)

to both sides of the equation, apply the boundary conditions at $x = 0$:

$$P(\tau) = -\lambda \frac{\partial t}{\partial x} \bigg|_{x=0} S$$

(4)

and transform Eq. (2)

$$\frac{\lambda}{l} \int_0^l \frac{\partial^2 t}{\partial x^2} dx = \frac{\lambda}{l} \int_0^l \frac{\partial}{\partial x} \left( \frac{\partial t}{\partial \tau} \right) = \frac{1}{l} \left[ \lambda \frac{\partial t}{\partial x} \bigg|_{x=l} - \lambda \frac{\partial t}{\partial x} \bigg|_{x=0} \right] = \frac{\rho c}{l} \int_0^l \frac{\partial t}{\partial \tau} dx = \frac{\rho c}{l} \frac{\partial t_v}{\partial \tau}.$$  

Here $t_v$ denotes the volume average temperature,

*We shall designate these heat gauges as "ordinary" in the remainder of the paper.


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Following transformation Eq. (2) takes the form

\[ P(\tau) = C \frac{dt_e}{d\tau} - \lambda S \left. \frac{dT}{dx} \right|_{x=l}. \] (6)

The last term in Eq. (6) can be expressed through the condition at the boundary \( x = l \). The surface \( x = l \) can dissipate heat into a vacuum, or to a gaseous or liquid medium, or it can be attached to the surface of a solid body. In other words, there can be boundary conditions of the third or fourth kind, i.e.,

\[ \frac{dT}{dx} \bigg|_{x=l} = \alpha (t_l - t_m), \quad \frac{dT}{dx} \bigg|_{x=l} = -\lambda \frac{\partial t}{\partial x} \bigg|_{x=l}. \] (7)

Equation (6) indicates that it is possible to measure a heat flux \( P(\tau) \) which varies with time, using heat gauges of this type. To do this one must know the variation of the volume average temperature \( t_V \) with time and the temperature gradient at the boundary \( x = l \) at different times.

We consider possible measurement of these quantities. Measurement of the average volume temperature of a gauge encounters more or less difficulty depending on the gauge structure, and, as a rule, requires some modification, since the heat gauge is constructed for possible measurement of temperature drop at its surface.

Measurement of the temperature gradient at the surface \( x = l \) is rather more complicated. One cannot measure this directly, but can only do so with the help of conditions (7). The following relations can be derived from Eqs. (6) and (7):

\[ P(\tau) = C \frac{dt_e}{d\tau} + \alpha S (t_l - t_e), \] (8)

\[ P(\tau) = C \frac{dt_e}{d\tau} - \lambda \frac{\partial t}{\partial x} \bigg|_{x=l}. \] (9)

It follows from Eqs. (8) and (9) that to determine the flux \( P(\tau) \), besides the variation of average volume temperature with time, one must measure either the temperature at the wall \( x = l \) and the temperature \( t_m \) of the surrounding medium, or the temperature gradient \( \frac{dT}{dx} \bigg|_{x=l} \) in the body to which the gauge is attached. In addition, one must know the parameters \( \alpha \) and \( \lambda T \) which describe the gauge operating conditions.

Although it is possible to measure the gradient \( \frac{dT}{dx} \bigg|_{x=l} \), there are major engineering difficulties. As regards the parameters \( \alpha \) and \( \lambda T \), these can be determined from calibration tests, but such tests are valid only for the conditions in which the test data are obtained.

Thus, analysis of Eq. (6) leads to the following conclusions:

- The measurement of a heat flux \( P(\tau) \) which varies with time cannot be made using formulas of type (1), obtained for steady conditions;
- ordinary heat gauges based on the auxiliary wall method are not well suited for the unsteady problem;
- the greatest difficulty in the measurement stems from determination of the last term in Eqs. (6), (8), and (9).

**Combination and RC Heat Gauges**

We consider a system of bodies consisting of an ordinary heat gauge 1 and a wall 2 separated from 1 by a gas gap 3 (Fig. 1b). In practice, this system can be implemented using a cap 2, attached to the gauge 1 and separated from it by a narrow gap 3 and insulating gasket 4 (Fig. 1c). We assume that we can measure the temperature difference \( \Delta t = t_1 |_{x=L_1} - t_3 |_{x=L_2} \), and then the last term in Eq. (6) can be put in the form