NONSTEADY CHANGES IN STRUCTURAL THERMOPHYSICS

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An experimental method is proposed for determining the damping of a harmonic temperature wave passing through the model of a real building construction. The rates of temperature changes at the inner surface of the wall are measured. Characteristic conditions and results of the experiment and the principle of operation of a specially designed thermal-conductivity meter are described.

Statement of the Problem

In view of the extensive use of light and thin encloser constructions in buildings a need has arisen for studying their thermal—technical characteristics. The thermal resistance R is a parameter that does not completely characterize the feasibility of use and quality of the encloser wall. The thermal resistance R combines the indices describing the behavior of the wall in nonsteady thermal processes.

One of the important indices for the summer season is the ability to suppress periodic temperature changes occurring in the surrounding medium and passing to the inner surface of the encloser.

The second index having a great significance in the winter season is the inner-surface cooling rate during an interruption in the heating. All these problems theoretically were studied in detail and solved exactly as a result of considerable successes of Soviet investigators in the field of applied structural thermophysics [1-7]. Czechoslovakian standards [8] and instructional literature [9] give instructions for simplified as well as for exact computation of damping of a harmonic temperature wave passing through a single- or multilayer wall designated as thermal damping:

$$\nu = A_e/A_{ip}.$$

In the standards an estimate is given for the minimum value of ν for different times of the year and orientation of the enclosing element. In [8, 9] a method of computing the relative temperature drop θ at the inner surface is given which determines the maximum decrease of the initial constant-temperature shear through 8 h of cooling under adiabatic conditions at the inner surface of the construction.

Although advances have occurred in the field of the theory, the experimental verification in the case of nonsteady and quasisteady temperature conditions is significantly lacking. This is accounted for by the following: First, unlike the experimental investigations of thermal resistance R, it is necessary to exactly determine and maintain the value of the heat-transfer coefficient α on both sides of the investigated model, i.e., on the outer and inner surfaces; second, it is necessary to specify the law of the temperature change at one or both sides of the model according to a definite program. In the case of investigation of ν it is necessary to ensure the harmonic law of temperature change rigorously at the outer side of the model; on the inner side it is necessary to have a linear law or create adiabatic conditions, i.e., zero thermal flux across the surface during the entire process of cooling at the outer surface. The object of this experimental investigation of the thermal damping ν, phase shift ε, and factor θ is to confirm the results of the computations, especially in those cases, when the mathematical analysis is very difficult. This leads to the basic requirement that the measured values of ν, ε, or θ be convenient for comparison with the values computed directly or not requiring mathematical analysis requiring the use of additional coefficients.

The equation for the exact computation of thermal damping of a single-layer wall has the form [7, 9]

$$\Theta = \left(\frac{\alpha_i}{\bar{z}} + \frac{\bar{z}}{\alpha_e}\right) S + \left(1 + \frac{\alpha_i}{\alpha_e}\right) C, \tag{1}$$

where

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$$S = \mathrm{sh}\left(\frac{d}{\lambda}\bar{z}\right); \quad C = \mathrm{ch}\left(\frac{d}{\lambda}\bar{z}\right); \quad \bar{z} = \left(i\frac{2\pi}{\tau_0}\lambda c\rho\right)^{1/2}.$$

From Eq. (1) we obtain the following expression for the absolute value of ν:

$$\nu = |\Theta| = (a^2 + b^2)^{1/2}, \tag{2}$$

where a and b are the real and imaginary parts of the complex number $a + bi$.

An analysis of (1) shows that for a direct comparison of the computed and measured values of ν and ε it is necessary to observe exact equality of all the terms of the equation. The case cited here pertains to α_i, α_e, and τ_0. Since the values of α_i, α_e, and τ_0 are normalized, in the experimental investigations of modern constructions it is necessary to observe these standard values, which means that the experiment should be conducted on a model 1 : 1 scale.

The only simplification (if τ_0 = 86,400 sec = 24 h) in relation to natural conditions remains the harmonic change of the air temperature at the input.

The results of experimental investigations have shown that the observance of the harmonic variation of the air temperature is simpler than sawtooth or even rectangular regimes. By regulating the transfer function it is easily possible to eliminate the effect of the specific heat not only of the intrinsic model but also of the measuring instrument. This is facilitated by a period equal to 24 h. The difficulty consists in maintaining the recommended values of α [α_i = 8.14 W/m$^2\cdot$°K, α_e = 23.26 W/m$^2\cdot$°K according to the existing Czechoslovakian State Standard (CSS) 73 05 40]. It is obvious that the model will work even in the case when α_i < 8.14 W/m$^2\cdot$°K, α_e > 23.26 W/m$^2\cdot$°K, because the value in the directive CSS 73 05 40 of ν_{min} = 8.34 is obtained for

$$8.34 < \nu\,[\alpha_e > 23.26; \ \alpha_i < 8.14].$$

Thus the result of the experiments indicates that the model works but is far from its existing mathematical description.

Since in practice it is not possible to expect complete exact correspondence of the values of α_i and α_e to the standards, we analyzed the effect of changes of these coefficients on the final value of ν.

The effect of change of α depends on the factor z of any wall and for direct comparison of the computed and measured values the following ranges of variation can be allowed: 17.45–29.00 W/m$^2\cdot$°K for α_e and 7.35–9.00 W/m$^2\cdot$°K for α_i. For α_i this is a very stringent requirement.

The following aspect, which must be kept in mind in conducting experiments, pertains to coefficient α, which only for the mathematical purposes is denoted as an overall coefficient considering the three components of heat transfer: convection, conduction, and radiation.

In the computation α represents a quantity taking account of all the forms of heat transfer; but in practice this can never be done. Even for a small difference of the air temperature t_v and model surface temperature t_p the radiational component can reach 25% and more of the values of α_i and up to 15% or more for the values of α_e, depending on the coefficient C.

The only secondary quantity is the mean temperature drop $t_e - t_i$. In specifying this quantity it must be remembered that for its low values (grad t → 0) the fraction of the reverse surface heat flux increases in the descending phase of the harmonic wave. For a sharp temperature drop this factor disappears but the computation must be carried out with large humidity transfer and change of coefficient λ, depending on the temperature difference.

The same conditions, which are necessary for ν and ε, are necessary also for the experimental investigation of the relative temperature drop. In this case α_i is the secondary (input) value and α_e must be maintained constant as well as the air temperature at the output (cold wall) t_e.

On the input (hot inner) side it is necessary to insure the condition $q(\tau) = 0$; i.e., $t_i(\tau) = t_{ip}(\tau)$. The initial drop $t_i - t_e$ must be specified in such a way that the given condition must be ensured for at least 8 h in compliance with the standard. This requirement must be considered in the construction of the measuring equipment.

Experimental Method

In practice the harmonic temperature change can be ensured by a mechanical cam or by using electronics. For ensuring sinusoidal variation of the temperature it is necessary to add to the input box certain specific blocks which are not used in the measurement of thermal resistance R.

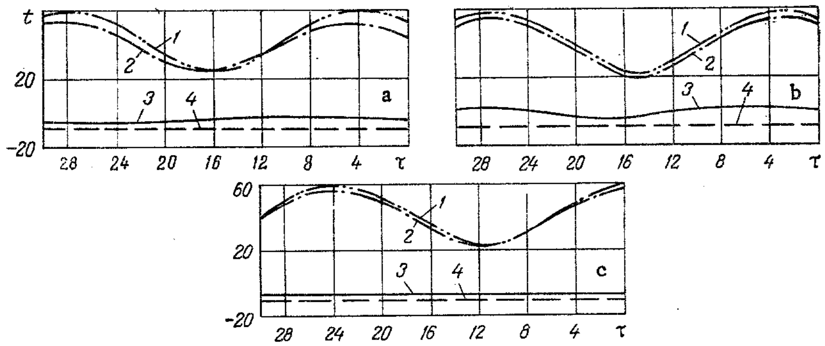

Fig. 1. Temperature variation in constructions of different materials (from right to left): a) ceramic panel (R = 1.2 m^2 · °K/W, ρ = 1150 kg/m^3, d = 0.39 m); b) insulation panel with mineral felt (R = 0.82 m^2 · °K/W, d = 0.04 m^2); c) insulation panel with mineral cotton wool (R = 2.37 m^2 · °K/W, d = 0.084 m); 1) variation of air temperature over the external surface t_e; 2) external surface temperature t_{ep}; 3) internal surface temperature t_{ip}; 4) internal air temperature t_i.

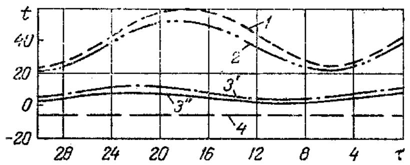

Fig. 2

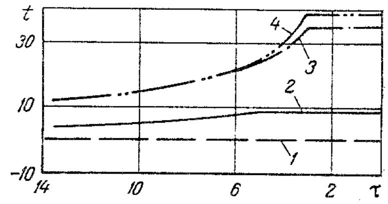

Fig. 3

Fig. 2. Temperature variation in the wall of hollow brick (R = 0.215 m^2 · °K/W, ρ = 1.550 kg/m^3, d = 0.135 m). Notation for the curves is the same as in Fig. 1.

Fig. 3. Temperature variation at cooling (as in Fig. 2) with adiabatic conditions over the external (warmer) surface (right to left); $t_i = t_{ip}$ during the cooling process, gradual fall of t_{ep} and stability of the outlet air temperature t_e. Duration of cooling is 10 h 15 min. Notation for the curves is the same as in Fig. 1.

The value of the coefficient α is determined mainly by the change in the convective component, i.e., the rate of circulation of the air flow along the investigated model. The circulation can be ensured by one or several series of propellers with regulated rotations of a diametral or radial ventilator. The central circulation systems do not ensure homogeneity of either α along the measured surface (1 m^2) or that of the rate of air flow and the surface-temperature drop; therefore they are not suitable.

The inverse estimate of the given coefficients α from the temperature difference between the air and the surface of the model, determined by thermal elements at both sides of the model, gives a systematic error due to its insensitivity to radiation. In this case the use of sensitive alpha-meter sensors is most suitable; these can be used in a set for the determination of the total values of α.

The recent models of alpha-meters are heat-compensated and record instantaneous absolute values of the coefficient α continuously.

The adiabatic conditions are ensured by using regulated heat flux at the surface and by holding its value at zero.

Results

The equipment for the measurements described above was built at the Heat-Engineering Laboratory of the Research and Experimental Institute of Factory Construction in Prague during 1966-1967 [10, 11].

The special thermal-conductivity meter of type AVG-2 is a two-chamber device with an independent control panel. The hot-input part for the measurement of the thermal resistance R is heat-compensated for the measurements of the values of ν and for θ it is "heat-open." The cold side is equipped with an assembly for holding the temperature exactly above or below 273°K.

In the first model there is a device for creating forced convection by circulation, consisting of two series of opposite propellers supplemented by different rotors and rectifiers of flow. In this equipment a series of measurements were made for the thermal damping (see Fig. 1, 2) and mean temperature drop (Fig. 3).

In spite of the difficulty and inadequate sensitivity of the control system, the harmonic law of temperature change at the input and the conditions were maintained so that in all cases of measurements $\alpha_e > \alpha_i$.

Although at the start of the first experiments the mean values of α in most series of tests were close to the recommended quantities, the absolute deviation in individual cases ranged from nearly −50% to +100%, especially for the values of α_i.

After an entire series of tests and improvements of the technique we succeeded in reducing the deviation of the values of α from those given above to smaller than −25% to +40%, and the difference between the measured and computed values of ν in general does not exceed ±18%.

The best agreement was obtained for the phase shift ε. It should be stressed that the deviations can be caused not only by individual inaccuracies in the changes of the boundary conditions but also by the fact that the initial data used for the computation (λ, c, ρ) do not exactly characterize the investigated construction. Similar disagreement of the experiment and computation can be expected even in future measurements.

In 1974 the construction of the measuring equipment was changed by introducing sensitive electronic units which insure a more rigorous observance of the boundary conditions than earlier.

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