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EXPERIMENTAL DETERMINATION OF THERMAL RADIATION PROPERTIES WHEN HEATING BODIES BY RADIATION IN A DIATHERMAL MEDIUM

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Аннотация—Предлагается новый метод определения характеристик теплового излучения, позволяющий достаточно быстро и точно определить оптические характеристики поверхностей тел, участвующих в лучистом теплообмене, угловые коэффициенты излучения, поверхностную плотность результирующего лучистого потока и поверхностную интенсивность аккумуляции тепла. Метод основан на аналитической обработке кривой прогрева исследуемого образца, полученной из опыта.

При определении оптических характеристик материалов конфигурация излучающей системы создается с заранее точно известными значениями угловых коэффициентов излучения. Это позволяет при проведении опытов в соответствии с разработанной методикой иметь надежный критерий для оценки правильности работы экспериментальной установки и точности полученных результатов.

NOMENCLATURE

A, absorption coefficient (absorptivity);
C, specific heat capacity of the material of the heated sample, kcal/kg degC;
E, surface density of radiant flow of integral radiation, kcal/m^2 h;
F, area, m^2;
r, half-thickness of the heated sample, m;
R, reflexion coefficient (reflectivity);
T, absolute temperature, degK.

Greek symbols

α, coefficient of convective heat transfer, kcal/m^2 h degC;
γ, volumetric weight of the material of the heated sample, kg/m^3;
τ, time, h;
φ, average (integral) angular radiation factor.

Subscripts

i, k, denote bodies or regions of bodies (of a zone) of the radiative system;
M, N, denote points;
m, denotes parameters of the medium surrounding the sample;
0, denotes parameters of an absolute black body;
res, shows that the resultant radiation is considered;
1, denotes values pertaining to radiators;
2, denotes values pertaining to the radiated sample;
3, denotes values pertaining to a conventionally concave body enclosing the considered system (this conventional body has $A_3 = 1$ and $E_{03} = 0$);
4, denotes values pertaining to bodies surrounding the system considered;
5, denotes values pertaining to lateral (not radiated) surface of the heated body.

INTRODUCTION

THE method proposed is a further development of the works of Luikov's school in this field [1, 2]. It is based on modern knowledge of the phenomenological theory of radiation and its application concerning the problems of calculation of radiative heat transfer in systems of grey bodies [3, 4], and differs from the methods of a similar study previously published, in the following ways:

(a) A more exact expression for determining surface density of resultant radiant flow of a heated body is derived and applied. It takes into account multiple reflexions and emission of radiant energy into the surrounding medium.

(b) Heat transfer from lateral surfaces of the heated sample and radiant energy gained from bodies surrounding the experimental set-up are taken into account.

(c) Design formulae are derived on the assumption that the known values of absorption coefficients for the surfaces of bodies under investigation are not equal to unity.*

(d) A greater number of values characterizing radiative heat exchange and design expressions is obtained: the methods are worked out for determining optical constants of surfaces of radiated bodies and radiators.

(e) A more nearly perfect technique of treating experimental data is used which substitutes graphic differentiation for an analytical one.

CALCULATIONS

Consider radiation of a uniform and isotropic sample (a radiated body or its model) in the form of a plate where $B_i < 0{\cdot}1$.

Radiation is obtained by two metallic radiating panels situated symmetrically relative to the radiated sample,† so that the origin of coordinates of the system is in the centre of this sample (Fig. 1). The supposition is made that surfaces of radiated samples and radiators in the problem considered are not concave or have such concavity that it may be neglected.‡

During radiation, a constant temperature is maintained on the radiator surface.

In the case to be discussed, the system of integral equations composed for the resultant radiation

$$\frac{E_{\text{res}}(M_i)}{A_i} - \sum_{k=1}^{n} \frac{R_k}{A_k} \int_{F_k} E_{\text{res}}(N_k)\, d\varphi_{M_i N_k} = \sum_{k=1}^{n} E_{0k}\varphi_{M_i F_k} - F_{0i} \quad (1)$$

may be substituted for the system of algebraic equations

$$E_{\text{res}\,i} - A_i \sum_{k=1}^{n} \frac{R_k}{A_k} E_{\text{res}\,k}\, \varphi_{ik} = A_i \sum_{k=1}^{n} E_{ki}\, \varphi_{ik} \quad (2)$$

[3, 4] where $d\varphi_{M_i N_k}$ is the elementary angular radiation factor, and $\varphi_{M_i F_k}$ is the local angular radiation factor [the subscript shows that we consider the angular factor of radiation from an elementary platform with point M of the body (zone) i, incident to the whole surface F of the body k visible from this platform].

In expression (2)

$$E_{ki} = E_{0k} - E_{0i}.$$

The system of algebraic equations (2) exactly describes the state of the radiating system if the geometry of it satisfies the condition

$$\varphi_{M_i F_k} = \varphi_{ik}(i, k = 1, 2 \ldots n). \quad (3)$$

If condition (3) is not strictly observed, the system of equations (2) represents an approximation of corresponding integral equations of

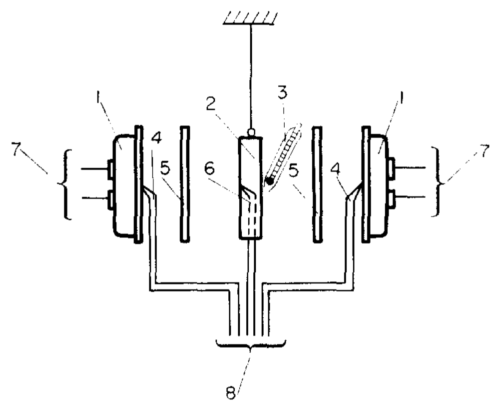

FIG. 1. Scheme of an experimental installation.
(1) radiators, (2) radiated sample, (3) screened thermometer, (4) radiator thermocouples, (5) screens, (6) thermocouple in the sample, (7) from the source of feeding of radiators, (8) to the potentiometer.

* Often, when smoking or colour covering is used, the coefficient of absorption of such bodies is supposed to equal unity. Sometimes, this assumption is responsible for perceptible errors.

† The reduction of the problem to a symmetric one leads to a simpler solution. When the methods proposed are applied to non-symmetric heating, the structure of initial and design expressions vary somewhat.

‡ It is by all means possible to develop and apply the methods to the case of concave grey bodies. Concavities may be taken into account in the final stages of calculation by substitution of eigenvalues for their effective quantities [4].

radiation. The essence of approximation lies in the fact that, instead of a real radiating system of any geometry and size with continuous fields of temperature and optical properties, a system is created and studied which consists of a finite number (n) of uniform, isothermal bodies (zones) having simple geometry. The degree of exactness of approximation is determined, on the one hand, by the value (n) and, on the other, by the degree of correspondence of the system's geometry to condition (3).

Solution of the system of equations (2) with respect to the particular problem considered, with the introduction of terms taking into account radiant-heat transfer from the lateral surface of the heated sample and from bodies surrounding the experimental set-up, leads to an expression for the surface density of the resultant radiant flow of the heated sample:

$$E_{\text{res }2} = A_2 \times \left[\frac{A_1\varphi_{21}(E_{01} - E_{02}) - (\varphi_{23} + R_1\varphi_{21}\varphi_{13})E_{02}}{1 - R_1R_2\varphi_{12}\varphi_{21}} - E_{02}\frac{F_5}{F_2} + A_4E_{04}\left(\varphi_{23} + \frac{F_5}{F_2}\right)\right]. \quad (4)^*$$

The resultant radiant flow is used for raising the heat content of the irradiated sample and for convective heat transfer from this sample to the surrounding medium.

Therefore we may write:

$$C\gamma r\frac{dT_2}{d\tau} = A_2 \times \left[\frac{A_1\varphi_{21}(E_{01} - E_{02}) - (\varphi_{23} + R_1\varphi_{21}\varphi_{13})E_{02}}{1 - R_1R_2\varphi_{12}\varphi_{21}} - E_{02}\frac{F_5}{F_2} + A_4E_{04} \times \left(\varphi_{23} + \frac{F_5}{F_2}\right)\right] - \alpha(T_2 - T_m)\left(1 + \frac{F_5}{F_2}\right). \dots \quad (5)$$

The left-hand side of equation (5) represents the surface intensity of heat accumulation (q_{acc}). The second term of the right-hand side takes into account convective heat transfer from the heated sample into the surrounding medium.

When the temperature of the radiators is considerably high (which is usually the case) compared to the temperature change of the sample heated, then we may assume that $E_{\text{res }2}$ does not change in the process of heating. Upon differentiation of equation (5), it is possible to obtain the expression for determination of the coefficient of convective heat transfer:

$$\alpha = \frac{-c\gamma r}{1 + F_5/F_2}\,\frac{d(dT_2/d\tau)}{dT_2}. \quad (6)$$

Assuming that T_1, T_4 and T_m do not change in the process of heating and making some simple transformations, we may give equation (5) in the following form:

$$dT_2 = [\beta - \mu T_2^4 - \nu(T_2 - T_m)]\,d\tau \quad (7)$$

where β, μ, ν are constant values.

Integrating equation (7) by the method of successive approximations, we obtain the equation of the heating curve in the third approximation, convenient for further treatment:

$$T_2 = k_0 + k_1\tau + k_2\tau^2 + k_3\tau^3 + k_4\tau^4 + k_5\tau^5. \quad (8)$$

Hence it is easy to obtain the expression for determination of the heating rate:

$$\frac{dT_2}{d\tau} = k_1 + 2k_2\tau + 3k_3\tau^2 + 4k_4\tau^3 + 5k_5\tau^4 \quad (9)$$

and also the derivative, entering expression (6), which determines the value of the coefficient of convective heat transfer:

$$\frac{d(dT_2/d\tau)}{dT_2} = \frac{2k_2 + 6k_3\tau + 12k_4\tau^2 + 20k_5\tau^3}{dT_2/d\tau}. \quad (10)$$

From this it may be concluded that if it is possible to obtain, from the experiment, the values of derivatives $dT_2/d\tau$ and $d(dT_2/d\tau)/d\tau_2$, then from expression (6) and equalities

$$q_{\text{acc}} = c\gamma r\frac{dT_2}{d\tau}$$

* Since bilateral symmetric heating is assumed, all the values in expression (4) refer to only one of the halves of the sample or system considered.

and

$$E_{\text{res } 2} = q_{\text{acc}} + \alpha(T_2 - T_m)\left(1 + \frac{F_5}{F_2}\right)$$

we may calculate the values of the coefficient of convective heat transfer, surface intensity of heat accumulation and surface density of the resultant radiant flow.

From equation (4), expressions may also be obtained for experimental determination of angular radiation factors and optical characteristics of the surfaces of the radiated sample and radiators.

Experiments on the determination of these values may be carried out under such conditions that the product $R_1R_2\varphi_{21}\varphi_{12}$ from equation (5), when compared with unity, is equal to zero. Under this condition, upon some simple algebraic transformations carried out with regard to the fact that

$$A_i + R_i = 1$$

and on the basis of the properties of reciprocity and closure

$$\varphi_{ik} \cdot F_i = \varphi_{ki} F_k \tag{11}$$

$$\sum_{k=1}^{n} \varphi_{ik} = 1, \tag{12}$$

expressions may be derived from equation (5) for determination of the values given above. They have the following form:

$$\varphi_{21} = \frac{\{-(A_1A_2E_{01} - A_2A_4E_{04}) + [(A_1A_2E_{01} - A_2A_4E_{04})^2 - 4R_1A_2(F_2/F_1)E_{02}(-D)]^{1/2}\}}{2R_1A_2(F_2/F_1)E_{02}} \tag{13}$$

$$A_1 = \frac{D - A_2\varphi_{21}(\varphi_{12}E_{02} - A_4E_{04})}{A_2\varphi_{21}(E_{01} - \varphi_{12}E_{02})} \tag{14}$$

$$A_2 = \frac{C\gamma r\, \mathrm{d}T_2/\mathrm{d}\tau + \alpha(T_2 - T_m)(1 + F_5/F_2)}{[R_1\varphi_{12}\varphi_{21}E_{02} + (A_1E_{01} - A_4E_{04})\varphi_{21} - (E_{02} - A_4E_{04})(1 + F_5/F_2)]} \tag{15}$$

where

$$D = C\gamma r \frac{\mathrm{d}T_2}{\mathrm{d}\tau} + [A_2E_{02} - A_2A_4E_{04} + \alpha(T_2 - T_m)](1 + F_5/F_2)$$

Equations (13–15) are of a general nature. It is easy to obtain from them simple expressions for various specific cases: $r \simeq 0$; $F_5 \simeq 0$; $A_1 \simeq 1$; $A_2 \simeq 1$, etc.

Often, for example, with the aim of simplification (without paying attention to the increase in the error) we assume that absorption coefficients of surfaces covered with soot are equal to unity. For this case, when $A_1 = A_2 \simeq 1$, we obtain from equation (13):

$$\varphi_{21} = \frac{\{C\gamma r\, \mathrm{d}T_2/\mathrm{d}\tau + [E_{02} + \alpha(T_2 - T_m) - A_4E_{04}](1 + F_5/F_2)\}}{E_{01} - A_4E_{04}}. \tag{16}$$

In the case of a lateral surface of the sample irradiated being small, as compared with the total surface, its influence may be neglected, and the latter expression will acquire a simpler form:

$$\varphi_{21} = \frac{C\gamma r\, \mathrm{d}T_2/\mathrm{d}\tau + E_{02} + \alpha(T_2 - T_m) - A_4E_{04}}{E_{01} - A_4E_{04}}. \tag{17}$$

In all the above expressions, the surface density of a radiant flow may be expressed through the temperature. For this purpose we use the relation

$$E_{0i} = \sigma_0 T_i^4$$

where $\sigma_0 = 4{\cdot}9 \times 10^{-8}$ kcal/m^2 h deg^4. Although the above expressions appear to be complex, they are easily solved with respect to the unknown quantity, upon substitution of known values and those obtained from experiment.

EXPERIMENTAL AND RESULTS

The experiments for determining all the values given above were carried out on the installation shown schematically in Fig. 1. An irradiated sample (2) was located between the radiators (1) in conformity with the conditions of radiation formulated above. A thermocouple (6), electrode diameter 0·1 mm, was placed inside the sample in immediate proximity to one of the radiated surfaces. The temperature of the medium surrounding the sample was measured either by a thermometer (3), protected from the immediate action of radiation, or by a specially made thermocouple. Heated metallic panels were used as radiators. Heating elements were made of ni-chrome wire hermetically sealed inside fire-proof plates. The feed to heating elements was carried out by alternating current of 127V. Temperature control was maintained by thermocouples (4), hot junctions of which were put inside the radiating panels. The diameter of electrodes of these thermocouples was 0·15 mm. For controlling the temperature, specially developed radiating and absorbing plates were attached to the surface of radiating panels along their perimeter.

Before switching off, installation screens (5) were placed between the radiated sample and radiators.

When experiments are conducted to determine angular radiation factors, it is necessary to know beforehand the value of optical characteristics of all the surfaces of bodies taking part in radiative heat exchange. The absorption coefficient of the surface of a radiated sample should be known in order to obtain that of the surfaces of radiators, and vice versa. This is easily fulfilled, and the small value of the product $R_1R_2\varphi_{12}\varphi_{21}$ may be obtained when smoking or colour covering of the corresponding surfaces is applied. The surface density of the resultant radiant flow and surface intensity of heat accumulation are determined as intermediate values in all cases when experimental data are evaluated.

Although values of angular radiation factors for any system may be calculated exactly from the known analytical dependences, it is, nevertheless, desirable to determine them experimentally before conducting experiments on the optical characteristics. We may, by comparison, draw conclusions as to the correctness of the installation work to get an idea about possible error. Reproduction and accuracy of the methods proposed are illustrated in Table 1, which gives data of eight experiments, carried out under equivalent geometric conditions, to determine angular radiation factors of the system. In these experiments, the radiators and radiated sample had the form of disks which were placed parallel to each other on a common normal going through their centres. Exact design value of the angular coefficient φ_{21} was calculated by the known formula and was 0·2995.

Table 1

Expt. no.	φ_{21} obtained experimentally	Deviation of the exptl. value from the calc. (%)
1	0·2903	3·07
2	0·3005	0·33
3	0·2968	0·90
4	0·3009	0·47
5	0·2906	2·97
6	0·3012	0·57
7	0·2881	3·81
8	0·3006	0·37

The results adduced in Table 1 accurately give the absorption coefficient of a number of rubber mixtures and rubberized fabrics used in the electric cable and rubber industry. The data obtained were then used to develop new experimental installations in industry for infra-red heating and vulcanization of rubber articles as well as of rubber coatings of electric cables. For application of the methods developed, it is necessary to follow the condition $B_i < 0{\cdot}1$ for a radiated sample. At the same time, it is known that rubber mixtures and rubberized fabrics have low coefficients of heat conduction. Therefore, when optical characteristics of rubber mixtures and rubberized fabrics are determined, the radiated samples are prepared in a specific way. A tin disk (108 mm dia. and 22 mm thick) is glued to plates by a thin layer of rubber. The plates (from 0·15 to 0·3 mm thick) are made out of the rubber mixtures or rubberized fabric to be tested. A copper–constantan thermocouple, with electrode dia. 0·1 mm, is inserted into the disk at a distance of 2 mm from one of its radiated surfaces. For determination of the influence of the tin-disk surface, a number of experiments were carried out in which the absorption coefficient of the surface of the tin plate was changed through a wide range. It turned out that the state of the surface of this plate did not influence the value of the determined absorption coefficient of any rubber mixture or rubberized fabric. The sample was suspended between the radiators before the beginning of each experiment. Its strictly symmetric setting was attained with the help of a slide gauge and internal gauge, by displacement of the arm of a bracket on which the tested sample was suspended. In all cases, the installation was heated for 2–3 h before the beginning of an experiment, until the temperature on the radiator surfaces was stabilized and levelled completely. Screens (5) obstructing the radiated sample were removed at the beginning of the experiment and a stopwatch was started. During the experiment the temperature of the heated sample was recorded simultaneously with time reading (started from the beginning of radiation), at first every 40–60 s and then considerably less frequently. In the intervals between these calculations, the temperature of the radiator and that of the medium surrounding the sample were recorded.

It is sufficient to carry out the experiment for 10–12 min to obtain the unknown values. However, as was shown in practice, it is more expedient to conduct an experiment for 50–60 min to simplify the calculation procedure for finding coefficients k of equation (8). The coefficients of equation (8) were determined from the recorded times of an experiment, the method of chosen points having been applied. The heating curve was then obtained from this equation. In all cases, the coincidence of experimental points with the theoretical curve was quite satisfactory, which proves the correctness of the chosen method of treating experimental data.

On verification of coincidence of empirical points with the theoretical heating curve, the values of derivatives

$$\frac{dT_2}{d\tau};\quad \frac{d(dT_2/d\tau)}{dT_2}$$

and the quantities α, q_{acc}, $E_{res\,2}$ were calculated.

Further, depending on the aim of the experiment, corresponding values were determined by formulae (13–15). The temperature of bodies surrounding the experimental set-up (walls, ceiling, floor, etc.) was assumed equal to room-temperature. The average absorption coefficient of these same bodies (A_4) was determined from the tables to be usually close to 0·9.

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Abstract—A new method is proposed, for the determination of thermal radiation properties, which allows prompt and exact determination of optical characteristics of the surfaces of bodies taking part in radiative heat exchange, as well as of angular coefficients of radiation, surface density of the resultant radiant flow and surface intensity of heat accumulation. The method is based on an analytical treatment of the curve obtained from a heated sample.

When optical characteristics of materials are determined, the geometry of the radiative system is taken from the values of angular coefficients of radiation known exactly beforehand. This provides a reliable criterion for estimating the correctness of an experimental installation and the accuracy of results obtained in experiments carried out in accordance with developed methods.

Résumé—L'auteur propose une nouvelle méthode de détermination des propriétés du rayonnement thermique qui permet d'obtenir, rapidement et exactement, les caractéristiques optiques des surfaces qui échangent de la chaleur par rayonnement, aussi bien que les coefficients angulaires de rayonnement, la densité du rayonnement résultant sur la surface et l'accumulation de chaleur. Cette méthode est fondée sur l'étude analytique de la courbe obtenue avec un échantillon chauffé.

Quand les caractéristiques optiques du matériau sont déterminées, la géométrie du système rayonnant est établie à partir des coefficients angulaires du rayonnement qui sont connus d'avance exactement. Ceci fournit un critère pour juger une installation expérimentale et l'exactitude des résultats obtenus dans les essais effectués avec les méthodes étudiées ici.

Zusammenfassung—Zur Bestimmung der thermischen Strahlungseigenschaften wird eine neue Methode vorgeschlagen. Sie gestattet die sofortige und genaue Bestimmung der optischen Charakteristika der am Strahlungsaustausch beteiligten Flächen, der Strahlungszahlen für verschiedene Winkel, der resultierenden Strahlungsstromdichten und der Wärmekapazitäten. Die Methode beruht auf der analytischen Auswertung einer Kurve, die sich für die entsprechende Probe aus einem Versuch ergibt.

Zur Untersuchung der optischen Charakteristika verschiedener Materialien wird die geometrische Anordnung des strahlenden Systems entsprechend den vorher genau bekannten Strahlungszahlen getroffen. Damit lässt sich auch die Zuverlässigkeit der experimentellen Einrichtung und die Genauigkeit der aus Experiment und Analyse erhaltenen Werte abschätzen.