DETERMINING EMISSIVITY AND TRUE SURFACE TEMPERATURE BY MEANS OF A PYROMETER AND AN ATTACHMENT

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We examine a method of measuring the true surface temperature by means of a pyrometer with an adiabatic attachment designed to eliminate the introduction of a correction factor for emissivity. We propose a method of determining the emissivity by means of two pyrometers with cold and adiabatic attachments. We present the formulas and the curve of the functions needed to design the attachments and to evaluate the errors of the method.

In measuring temperatures by methods of radiation or optical pyrometry, we must introduce correction factors for the emissivity of the object measured, and this in most cases can be estimated only very approximately [1], We know of a method to measure surface temperatures by means of a pyrometer with a hemispherical mirror attachment designed to eliminate the need for correction factors for the emissivity of the material [2]. According to this method, the measurement is accomplished with a pyrometer with an attachment that is set almost flush with the object (Fig. 1). In this case, as a consequence of repeated reflection and reradiation within the closed system formed by the plane of the object and the attachment, somehow forming a model of a perfect black body, the object will radiate into the cavity of the radiometer with an emissivity close to unity. However, no indication is given in [1] of how to measure – with this procedure – the true temperature in the presence of reflectors and oblique emitters that are more powerful than the emission of the object itself (for example, when heating an object in a furnace), nor are there any data on the measurements, design, and other characteristics of the attachment, nor any estimates of the errors that are functions of the characteristics of the attachment and of the parameters of the ambient medium.

It is obvious that this proposed method can also be extended to those temperature-measurement cases in which the object is surrounded by reflectors and emitters and in which it is virtually impossible to provide for the introduction of any correction factors. Because of the reflected flows that are more powerful than the natural radiation of the object itself, the correction factor for the "emissivity" of the object as it is heated by radiation, for example, in a furnace, may turn out to be even greater than unity.

On the basis of our use of a pyrometer with an attachment we can propose a simple method of determining the emissivity from the relationship between two heat flows

$$\varepsilon = \frac{E}{E_0}, \tag{1}$$

where E and E_0 are the heat flows, respectively, measured by means of the pyrometer without an attachment at the beginning, with no side emitters or reflectors about the object, and then with an attachment.

In analogy with the model of a perfect black body, the extent to which the surface ε approaches unity in measurements with a pyrometer and an attachment will probably depend on the geometric dimensions and the parameters of the system formed by the object, the attachment, and the pyrometer. To evaluate the errors in determining the temperature and the emissivity by the above methods, we must therefore perform the calculations for such a system, i.e., we have to determine the shape and dimensions of the attachment

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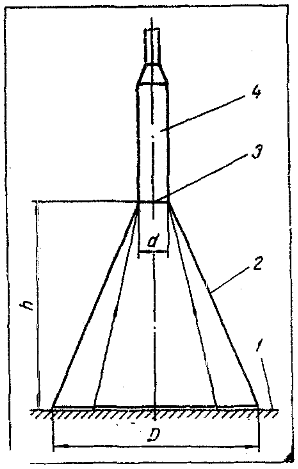

Fig. 1. Diagram for the derivation of the equations for attachment design: 1) surface of object being measured; 2) adiabatic attachment; 3) pyrometer orifice; 4) pyrometer.

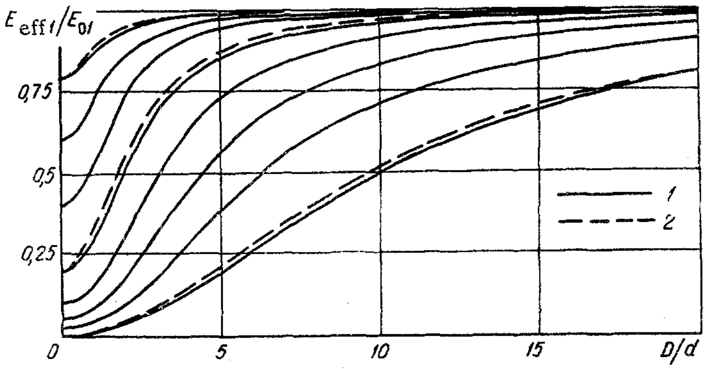

Fig. 2. The dependence of E_{eff1}/E_{01} on the system parameters D/d, h/d, and a_1.

for a given pyrometer with an inlet orifice d, to ensure the required methodological accuracy in determining the T of the object and the ε of its material.

To find the relationship with which to calculate the dimensions of the attachment, let us examine the closed system (Fig. 1) consisting of three elements: the surface 1 of the object being measured, bounded by the edge of the attachment whose diameter is D and which exhibits the parameters $\varepsilon_1(a_1)$ and T_1; then we have attachment 2 which is conical in shape, or of some other shape, supported on circles with diameters D and d, a height h with $\varepsilon_2(a_2)$, and T_2; and finally, the surface 3 of the inlet orifice for the pyrometer, with a diameter d, and the parameters $\varepsilon_3(a_3)$ and T_3.

By definition, the surface of the measured object (1) is the source of radiant energy in the system, with an intrinsic flow $E_1 = \varepsilon_1\sigma_0 T_1^4$. The inlet orifice for the pyrometer completely absorbs the radiant flow and does not radiate, so that $\varepsilon_3 = a_3 = 1$ and $T_3 = 0$ and, consequently, we have $E_3 = 0$ and $E_{eff3} = 0$. We assume the surface of the attachment to be adiabatic, i.e., the entire radiant flux incident on the attachment is reflected by the latter and reradiated both on the inside and the outside of the system. The viewing area of the pyrometer must be smaller than the area of the object bounded by the attachment, and the attachment itself must completely cover the object.

We assume that: 1) within the limits of each surface T and $\varepsilon(a)$ are constant, and also that $\varepsilon = a$; 2) the temperature of the measured surface 1 of the object does not change on approach of the device with an attachment.

Under ordinary conditions, the pyrometer picks up the natural radiant heat flow of the object within the field of view. When the emitting–reflecting adiabatic attachment is brought close to the object, because of the repeated reflection and reradiation between the attachment and the object, the reflected flow is added to the natural flow, so that the pyrometer will receive an effective flow $E_{eff\,1} = E_1 + E_{ref1}$. Of course, with an increase in attachment dimensions the value of $E_{eff\,1}$ will tend toward E_{01}. The equation

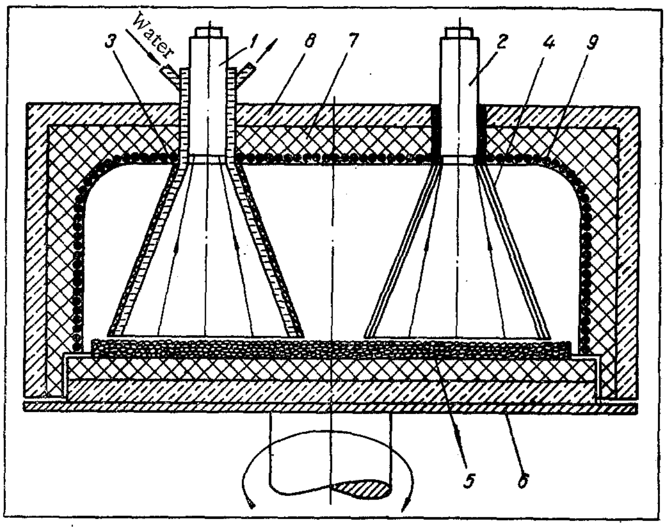

Fig. 3. Installation for the determination of emissivity: 1 and 2) pyrometers; 3) cold attachment blackened on the inside; 4) adiabatic attachment; 5) circular plate or layer of test material; 6) rotating disk with refractory and heat-insulation layers; 7) refractory wall of heating chamber; 8) heat-insulation layer; 9) electric heater.

for the effective radiation of the i-th surface of the closed system, consisting of n surfaces, will have the following form [3]:

$$E_{\mathrm{eff}\,i} = (1 - a_i) \sum_{k=1}^{n} E_{\mathrm{eff}\,k} \varphi_{ik} + E_i. \qquad (2)$$

In our case, for each of three surfaces we will have a system of three equations:

$$E_{\mathrm{eff}1} = (1 - a_1)(E_{\mathrm{eff}1}\varphi_{11} + E_{\mathrm{eff}2}\varphi_{12} + E_{\mathrm{eff}3}\varphi_{13}) + E_1, \qquad (3a)$$

$$E_{\mathrm{eff}2} = (1 - a_2)(E_{\mathrm{eff}1}\varphi_{21} + E_{\mathrm{eff}2}\varphi_{22} + E_{\mathrm{eff}3}\varphi_{23}) + E_2, \qquad (3b)$$

$$E_{\mathrm{eff}3} = (1 - a_3)(E_{\mathrm{eff}1}\varphi_{31} + E_{\mathrm{eff}2}\varphi_{32} + E_{\mathrm{eff}3}\varphi_{33}) + E_3. \qquad (3c)$$

Since by definition $T_3 = 0$, $a_3 = 1$, and $E_3 = 0$, we have $E_{\mathrm{ref}\,3} = 0$ and $E_{\mathrm{eff}3} = 0$, and in addition, from the adiabaticity condition for surface 2, i.e., the entire incident flow on the surface is reflected or reradiated as a consequence of surface heating, we can assume that $a_2 = 0$ ($r_2 = 1$) and $E_2 = 0$. In this case, we refer the reradiated flow to the reflected flow, making the assumption that $T_2 = 0$. From the properties of the angle factors for flat surfaces we find that $\varphi_{11} = 0$, and $\varphi_{33} = 0$. After simplification, the system of equations (3) assumes the form

$$E_{\mathrm{eff}1} = (1 - a_1) E_{\mathrm{eff}2}\varphi_{12} + E_1, \qquad (4a)$$

$$E_{\mathrm{eff}2} = E_{\mathrm{eff}1}\varphi_{21} + E_{\mathrm{eff}2}\varphi_{22}. \qquad (4b)$$

We calculate the angle factors φ_{12}, φ_{21}, φ_{22} on the basis of the known dependence of φ_{13} for two circles of diameters d and D, lying in parallel planes with centers on a common normal, separated by a distance h [3], using the properties of closure and reciprocity for the angle factors:

$$\varphi_{12} = 1 - \varphi_{13}, \qquad (5a)$$

$$\varphi_{21} = \frac{F_1}{F_2}\varphi_{12} = \frac{F_1}{F_2}(1 - \varphi_{13}), \qquad (5b)$$

$$\varphi_{22} = 1 - \varphi_{21} - \varphi_{23} = 1 - \frac{F_1}{F_2}(1 - \varphi_{13}) - \frac{F_3 - \varphi_{13}F_1}{F_2} = 1 - \frac{F_3}{F_2} - \frac{F_1}{F_2}(1 - 2\varphi_{13}), \qquad (5c)$$

where $F_1 = \pi D^2/4$, $F_2 = \pi d^2/4$, and $F_3 = [\pi(D + d)/2]\sqrt{h^2 + [(D-d)/2]^2}$ are the areas of surfaces 1, 2, and 3, respectively.

After solving the system of equations (4) and (5) for E_{eff_1}/E_{01} and E_{eff_2}/E_{01} we have

$$\frac{E_{eff1}}{E_{01}} = a_1 \frac{1-\left(\frac{D}{d}\right)^2 \varphi_{13}^2 + \left(\frac{D}{d}\right)^2 (1-\varphi_{13})^2}{1-\left(\frac{D}{d}\right)^2 \varphi_{13}^2 + a_1 \left(\frac{D}{d}\right)^2 (1-\varphi_{13})^2}, \tag{6a}$$

$$\frac{E_{eff2}}{E_{01}} = a_1 \frac{\left(\frac{D}{d}\right)^2 (1-\varphi_{13})^2}{1-\left(\frac{D}{d}\right)^2 \varphi_{13}^2 + a_1 \left(\frac{D}{d}\right)^2 (1-\varphi_{13})^2}, \tag{6b}$$

$$\varphi_{13} = \frac{1}{2}\left\{1+\left(\frac{d}{D}\right)^2 + \left(2\frac{h}{D}\right)^2 - \sqrt{\left[1+\left(\frac{d}{D}\right)^2+\left(2\frac{h}{D}\right)^2\right]^2 - 4\left(\frac{d}{D}\right)^2}\right\}. \tag{7}$$

Analysis of (6) and (7) shows that E_{eff_1}/E_{01} consists of two cofactors and seemingly represents the emissivity of the system, while E_{eff_2}/E_{01} is that fraction of the energy from E_{01} reflected by the attachment of surfaces 1 and 3. In all cases $0 \leq E_{eff_1}/E_{01} \leq 1$ and $0 \leq E_{eff_2}/E_{01} \leq 1$. With our assumptions E_{eff_1}/E_{01} and E_{eff_2}/E_{01} are determined exclusively by the parameters a_1, D, d, h, and they are independent of the shape of the attachment, since the final equations (6) do not include the attachment area F_2. From the standpoint of approaching the conditions of adiabaticity and increasing the reflection coefficient for the attachment, as well as from the standpoint of simplicity of fabrication, it would therefore be most convenient to have a conical shape, rather than one that is spherical or of some other shape. When $a_1 = 1$, the second cofactors in (6) are changed to unity and E_{eff_1}/E_{01} and E_{eff_2}/E_{01} thus do not depend on the dimensions of the attachment, as was to be expected.

Numerical computer calculations were based on (6) and (7); we then plotted the curve for the functions $E_{eff_1}/E_{01} = f(D/d,\ h/d,\ a_1)$ (Fig. 2). We see from the figure that the emissivity of the system, or the ratio E_{eff_1}/E_{01}, is a strong function of the relative attachment dimension D/d and increases as the latter increases, approaching unity; it depends only slightly on the parameter h/d. The smaller the emissivity $\varepsilon_1(a_1)$ of the surface material, the greater the attachment's surface dimensions D/d have to be to achieve the same accuracy in bringing E_{eff_1}/E_{01} close to unity.

In designing the attachment we must know its basic characteristics, and here we should strive to reduce its dimensions, primarily D/d, since this serves to reduce the measurement area and, consequently, we can measure the T_1 and $\varepsilon_1(a_1)$ of an object with smaller dimensions; in addition, we reduce the error which is brought about by the change in body temperature as the attachment is brought near. Proceeding from the possible limits of $\varepsilon_1(a_1)$ and the required accuracy in bringing E_{eff_1}/E_{01} to unity, we therefore determine the minimum dimensions D/d from the curve in Fig. 2. Although h/d has virtually no effect on E_{eff_1}/E_{01} and on the basis of our assumptions the temperature T_1 in the derivation of the equations must be identical over the entire surface 1, in actual fact, with a small h/d the cold surface 3 – as a consequence of shielding – disrupts the condition of isothermicity for surface 1 [4]. To avoid such dimensions, the attachments have to be chosen so that $h/d > D/d$.

If the attachment is intended to measure the brightness temperature or $\varepsilon_\lambda(a_\lambda)$, we will carry out the calculation in the same manner, but in this case E must be replaced by the spectral emission intensity b_λ. However, if the emission of the body is selective in nature and we have $a \neq \varepsilon$ and $\varepsilon_\lambda(a\lambda) = f(\lambda)$, we will carry out the calculation for specific intervals $\Delta\lambda$ and we will find that

$$E_{eff1}/E_{01} = \int_{\lambda=0}^{\lambda=\infty} b_{\lambda eff1}/b_{\lambda 01}(\lambda)d\lambda \cong \sum_{n=1}^{n=\infty} b_{\lambda eff1}/b_{\lambda 01}(\lambda_{n-1}-\lambda_n). \tag{8}$$

For our model of a perfect black body – the surface–attachment system – in measuring E_{eff_1} we must necessarily have $T_1 = T_2$, as in the case of conventional models. On the basis of the conditions which we adopted in the derivation of the equations, surface 2 must be adiabatic, i.e., it must completely return the radiant flux incident on it, whether from within or from without. In practical terms, this is achieved by making the attachment so that it exhibits minimum losses to the ambient medium, i.e., by choosing a material for the attachment with the greatest possible r_2 and building it up out of several screens. If we assume that the losses δ to the ambient medium are functions of E_{eff_2}, i.e., $E_{eff_2} = \delta E_{eff_2}$, the error in the determination of E_{eff_1}/E_{01} will also be δ, since according to the calculations involving (6) on a computer, as $E_{eff_1}/E_{01} \to 1$ we can assume with sufficient practical accuracy that $E_{eff_2}/E_{01} \to 1$. Since [3]

$$E_2 = a_2 E_{\text{eff}2} - r_2 E_{\text{res}2}, \qquad (9)$$

after substitution of E_{res_2} into (9), neglecting δr_2, we have

$$E_2 = a_2 E_{\text{eff}2} - \delta r_2 E_{\text{eff}2} \cong a_2 E_{\text{eff}2} \cong a_2 E_{\text{eff}1}, \qquad (10)$$

whence

$$T_{2\text{in}} = \sqrt[4]{\frac{a_2}{\sigma_0} E_{\text{eff}1}}. \qquad (11)$$

Proceeding from T_{2in} and from the permissible losses δE_{eff_2} to the ambient medium, we calculate the number of streams that are needed, on the basis of the familiar relationships given in [3]. The screen should be made of a thin material, with the largest possible r_2, since the greater r_2, the fewer screens required. Morever, when the operating conditions of the attachment call for it to be heated to high temperatures, a heat-resistant material must be chosen to withstand this temperature.

Let us examine the method of determining emissivity by means of a pyrometer with an attachment. There are several methods of determining the ε of materials. Of these, the most practical and most common is the method of heat-flux ratios [5], according to which the intrinsic heat flow of the object – integral or spectral, hemispheric or angular (including normal), depending on how ε is defined [5] – is compared with the emission of a perfect black body with a surface temperature T. The value of E_0 is usually determined from the temperature measured by means of the thermocouple imbedded into the surface of the test material, or it is measured in a hole drilled into the specimen – the model of a perfect black body. The necessary condition in this case is that the temperatures of the inside cavity and of the surface are equal, which in the light of the temperature gradient through the thickness is complex to achieve under practical conditions and is applicable to materials exhibiting high thermal conductivity.

The proposed method of determining ε is based on the heat-flux ratio for an intrinsic and a perfect black body at the specimen surface temperature measured with a pyrometer using an adiabatic attachment. The advantages of the method lie in the fact that there is no need to imbed a thermocouple nor to drill a perfect black-body hole into the specimen. The attachment of the thermocouple at the surface of a flat specimen introduces an additional error, since it disrupts the conditions of heat transfer. In many cases, it is completely impossible to attach a thermocouple or to drill a hole, e.g., in determining the ε of thin-layer coatings, soot or ash deposits, coatings or enamels, ceramics, and various surfaces of complex structure [6]: finned or porous surfaces, including porous radiation burners, the surfaces of free-flowing or fluidized beds, and also in the determination of the effective value for ε, by means of which we account for the nonuniformity in temperatures through the depth of the microcavities at the specimen surface.

A drawback of the proposed method is the change in surface temperature which results as the pyrometer and the attachment are brought close to the object in measuring E_0. This drawback can be eliminated in brief measurements of E_0 or in the case of a moving object, e.g., in the case of a fluidized bed, when the particles at the surface are rapidly replaced, so that they cannot cool off. In this connection, to retain constancy of temperatures for objects with flat or rough surfaces, we can recommend the following device (Fig. 3). A circular plate or a layer of test material is positioned on a rotating heat-insulated disk, placed inside a heating chamber. Two identical pryometers with attachments are passed into the chamber through an orifice and are directed at the disk with the test material. One of the parameters is water-cooled and blackened on the inside. Its function is to shield the eyepiece of one of the pyrometers and to completely absorb the radiant flux from the plate. In this case, the pyrometer measures the natural radiant flow of the material. The other attachment – the adiabatic one – is made to satisfy the requirements stated above. Because of the rapid rotation of the disk and the test material on it, the temperature stays constant over the entire surface, including those segments directly beneath the attachments.

In designing a cold attachment there is no longer any need to satisfy the requirements imposed on the adiabatic attachment; in this case, we need only satisfy the condition that D is larger than the diameter of the eyepiece and that the inside surface of the attachment completely adsorbs the flux incident on it, without any radiation. The advantages of the device and of the method also lie in the fact that uniform heating of the material through its thickness is achieved within the chamber, which is particularly important for nonheat-resistant materials exhibiting low thermal conductivity, i.e., ceramics, glass ceramics, insulation materials, and the like. The usual methods of determining ε call for the unilateral heating of the specimen plate. This is difficult to achieve for such materials, since it is impossible, because of the high thermal resistance, to raise the temperature of the surface facing the pyrometer above some limit, as well as because of the fact that the specimen is not heat resistant and may be destroyed.

It is obvious that with slight structural changes we can use this device to determine the spectral, integral, normal, or hemispherical emissivity of the material.

Let us evaluate the error of the method in relation to the parameters of the attachment. From (6) we find the relative error in the determination of E_{eff1} as a function of the nonadiabaticity of the attachment surface 2, i.e., as a function of the heat losses from the attachment to the ambient medium:

$$\delta E_{eff1} = \delta E_{eff2}. \tag{12}$$

From the condition for the determination of the emissivity

$$\varepsilon = \frac{E_1}{E_0} = \frac{E_1}{E_{eff1}} \tag{13}$$

we find the relative error in the determination of ε, i.e.,

$$\delta\varepsilon = \delta E_{eff1} \tag{14}$$

and for the temperature, from the equation

$$E_{eff1} = E_{01} = \sigma_0 T^4 \tag{15}$$

we have

$$\delta T = 0.25\,\delta E_{eff1}. \tag{16}$$

The method of determining ε was tested on oxidized surfaces of copper, brass, and Duralumin, in limits from 200 to 450°C. We studied nine conic attachments of various dimensions D/d = 1-10 and h/d = 1-10. For the pyrometer we took a universal acute-angle total-radiation radiometer probe designed by the Gas Institute of the Academy of Sciences of the Ukrainian SSR with d $\simeq$ 15 mm [7]. A flat heater was used to heat the specimen plates on one side. For comparison with the classical method, thermocouples were imbedded on the specimen surfaces. Tests with various attachment dimensions confirmed the theoretical curves (Fig. 2). The results from the determination of ε for the test materials are close to those cited in the literature. This method was also used to determine the emissivity of a fluidized bed [8] and to measure the temperature of items heated within a furnace.

NOTATION

E	is the intrinsic radiant heat flux, W/m^2;
b_λ	is the spectral radiation intensity, W/m^3;
λ	is the wavelength, m;
T	is the absolute temperature, °K;
$\sigma_0 = 5.68 \cdot 10^8$	$W/m^2 \cdot deg^4$;
ε	is the emissivity;
a and r	are, respectively, the coefficients of absorption and reflection;
d, D, and h	are the geometric dimensions of the attachment, i.e., the orifice diameter on the pyrometer side, the same from the side of the object's surface, and the height, respectively, m;
F	is the surface area, m^2;
φ_{ik}	is the angle factor from surface i to surface k;
δ	is the relative error.

Subscripts

1, 2, and 3	denote the surface numbers, see Fig. 1;
0	pertains to absolute black-body radiation;
in	pertains to the inside surface;
eff	pertains to the effective radiant flow;
res	denotes the resulting flow;
ref	denotes the reflected flow.

LITERATURE CITED

1. D. Ya. Svet, Objective Methods of High-Temperature Pyrometry with a Continuous Emission Spectrum [in Russian], Nauka, Moscow (1968).
2. Land, Rev. Sci. Instruments, 26, 904 (1955).

3. A. S. Nevskii, Radiative Heat Exchange in Metallurgical Furnaces and Boilers [in Russian], Metallurgizdat, Sverdlovsk (1958).
4. A. I. Chernogolov, Thermometric Investigations of Open Hearth Furnaces [in Russian], Metallurgiya, Moscow (1967).
5. M. A. Bramson, Infrared Radiation from Heated Bodies [in Russian], Nauka, Moscow (1964).
6. S. G. Agababov, Teplofizika Vysokikh Temperatur, 6, No. 1 (1968).
7. V. S. Pikashov, O. A. Gerashchenko, L. S. Pioro, and G. V. Ryabchenko, "The universal acute-angle total-radiation radiometer probe," Inf. Pis'mo Instituta Gaza Akad. Nauk UkrSSR, No. 11, (98), Naukova Dumka, Kiev (1967).
8. V. S. Pikashov, S. S. Zabrodskii, K. E. Makhorin, and A. I. Il'chenko, Transactions of the Third All-Union Conference on Heat and Mass Transfer, Vol. 5 [in Russian], (1968), p. 303.