DIRECTIONAL EMISSIVITY OF STRUCTURAL MATERIALS

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Test data have been obtained on the integral emissivity of materials for various temperatures and surface states.

To perform accurate heat-engineering calculations of radiant heat transfer in power equipment one needs detailed radiative characteristics of structural materials. The present study investigates the integral directional emissivity of materials when heated in air.

The directional radiative properties of a material are described by the thermal radiative intensity

$$I = \frac{dq(\Theta)}{dF\cos\Theta\, d\omega}. \tag{1}$$

For a perfect black body the radiative intensity remains constant, independent of direction (Lambert's Law) [1]. The integral directional emissivity of the surface of a material is defined by the relation

$$\varepsilon(\Theta) = I(\Theta)/I^0. \tag{2}$$

For a given value of the product $dF\cos\Theta d\omega$, determining the emissivity $\varepsilon(\Theta)$ reduces to finding the ratio of the thermal radiative heat flux of the specimen to that of a perfect black body:

$$\varepsilon(\Theta) = dq(\Theta)/dq^0(\Theta). \tag{3}$$

The arrangement of the working section to measure the directional emissivity (by the radiative method) is shown in Fig. 1. The angle Θ between the normal to the specimen surface 1 and the direction of the radiation is generated by rotating the specimen along with the heating element around the point O_1. Simultaneously we rotate the diaphragm 3 around the point O_2 by the same angle Θ. It is rotated in order to change the visible part of the radiating area in proportion to the cosine of Θ. The cooled collimator tube 2 serves to avoid heating of the rotating diaphragm 3. The mirror 4 focuses the heat flux on the thermal column 5, located in a cooled jacket. Temperature control of the system for cooling the collimator tube and the thermal column jacket is accomplished by means of an ultrathermostat. In calibrating the equipment, besides the specimen 1 we set up a graphite high-temperature model of a perfect black body. In the calibration we do not rotate the radiating cavity of the black body, since it is known that the radiative density of a perfect black body in unit solid angle is independent of direction [1], but the diaphragm 3 is rotated through the angle Θ. In calibrating with the perfect black body and in measuring heat flux from the specimens we maintain equal projected areas of the apertures of diaphragm 3 in the direction O_1O_2. The surface temperatures of the specimens and the perfect black body are measured with Chromel—Alumel thermocouples with a thermal electrode diameter of 0.2 mm. The thermal emf is recorded by a type VK2-20 digital voltmeter. Thus, by rotating the heated specimen, along with the heater element and the diaphragm around axes O_1 and O_2 by different angles relative to the optic axis of the equipment and determining the emissivity as the ratio of the measured heat flux of the specimen to the calibration radiative flux of the perfect black body, at the same temperatures and with other conditions equal, we can obtain the dependence $\varepsilon = f(\Theta)$.

The surfaces of the materials used in the tests were isotropic. Besides the temperature the parameters governing the radiative properties of solids include the roughness and

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TABLE 1. Characteristics of the Test Specimen Surfaces

Material	Surface state	Roughness	
		R_a, μm	S_m, mm
19ChrMnNi	Ground on an emery wheel and oxidized in air at 750°K for 1 h	5,0	0,15
St3 steel alloy	Rolled sheet, oxidized in air at 850°K for 1 h	3,4	0,10
40Chr2Ni2MoAl	Rolled sheet, oxidized in air at 750°K for 1 h	3,0	0,17
Copper Mo3	Rolled sheet, oxidized in air at 850°K for 1 h	2,3	0,10
Aluminum alloy AlMn	Rolled sheet, oxidized in air at 750°K for 1 h	1,8	0,60

the presence of an oxide film. For a numerical description of specimen roughness we took the parameters R_a, the arithmetic average deviation of the roughness profile, and S_m, the average pitch of the profile roughness. The values of these parameters were measured on a type MIS-11 double microscope. The surface characteristics of the material specimens investigated in terms of oxidation level and roughness are shown in Table 1. The integral directional emissivity data obtained for these specimens at specific temperatures are shown in Table 2 as a function of the angle Θ.

It can be seen from Table 2 that of the specimens investigated the emissivity varies most strongly as a function of the angle Θ for the Al—Mn alloy. In the region of angles Θ = 20-30° for the Al—Mn alloy and also for Mo3 copper we observe minimal values of the directional emissivity. This may be due to the influence of roughness on the radiative properties of these specimens. For steel less deviation from Lambert's law is observed. With deep preparation of the surface the radiation becomes more diffuse. For the specimens investigated at the same temperatures the results for ε(Θ) obtained after the first and repeated heating differ only within the experimental accuracy. Practically at the end of the first heating a film of oxides forms and completely determines the nature of the emissivity as a function of radiation direction.

In technological processes it is very important to know the variation of radiative properties of metals as a function of the rate of initial heating. The growth of oxide film thickness during the first heating depends on the temperature level. For steel, as can be seen from Table 3, the sharpest variation of ε(Θ = 0) occurs in the temperature range 700-800°K. The variation of emissivity here is associated with the thickness of the oxide film, since the radiative power of oxides is an order higher than that of pure metals. Besides temperature, the rate of formation of the oxide film is affected by the original state of the specimen surface. As can be seen from Table 3, for St3 steel alloy preliminary

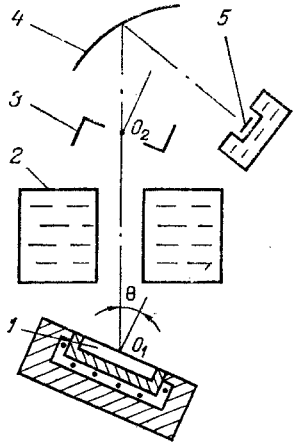

Fig. 1. Diagram of the working section.

TABLE 2. Integral Emissivity of Materials as a Function of the Direction of the Thermal Radiation

Material	Angle θ, deg										
	0	10	20	30	40	50	60	70	75	80	85
19ChrMnNi at 910°K	0,91	0,90	0,91	0,92	0,93	0,93	0,91	0,85	0,86	0,83	0,81
St3 steel alloy at 900°K	0,86	0,85	0,84	0,83	0,83	0,83	0,83	0,85	0,93	—	—
40Chr2Ni2MoAl at 940°K	0,65	0,65	0,65	0,64	0,63	0,62	0,60	0,56	0,55	0,58	0,61
Mo3 copper at 910°K	0,60	0,53	0,52	0,53	0,55	0,56	0,57	0,66	0,72	—	—
Al-Mn alloy at 780°K	0,27	0,15	0,11	0,12	0,13	0,14	0,20	0,40	0,60	—	—

preparation of the surface in hydrochloric acid for 55 min has a strong influence on the emissivity up to temperatures of about 600°K. An appreciable influence of surface preparation of St3 steel alloy in sulfuric acid is observed only for temperatures around 400°K. The fresh mechanical preparation of a steel surface on an emery wheel appreciably affects the emissivity values as a function of temperature up to 700°K.

The growth of oxide film on a metal surface increases its radiative power until the generation of thermal radiation is included within the thickness of the oxide layer. In that case the temperature dependence of the emissivity of the oxidized metal is determined by the optical constants of the oxide film material. A general tendency of most oxides is to decrease emissivity with increase of temperature. Therefore, for the Al—Mn alloy (see Table 3) one can observe some decrease of emissivity in the temperature range 500-700°K. This type of law for variation of emissivity as a function of temperature has been noted for another aluminum alloy, D16, in [1].

The error in measuring the integral emissivity is ±4.8-5.7%, depending on the kind of specimen, the angles θ and the temperature.

NOTATION

I, I^0, radiative intensity of the surface of a specimen of the material and of a perfect black body; dq, radiative flux element; θ, angle between the normal to the surface and the radiation direction; dF, area of the radiating element; dω, solid angle; ε, integral emissivity; R_a, arithmetic mean value of the deviation of the roughness profile, μm; S_m, mean pitch of the roughness profile, mm; T, temperature, °K.

TABLE 3. Integral Normal Emissivity of Metal Sheets after Heating in Air at an Average Rate of 17 deg/min

Grade	R_a, μm	S_m, mm	Temperature T, °K						
			400	500	600	700	800	900	1000
St3 steel alloy	1,5	0,05	0,67	0,68	0,73	0,76	0,85	0,86	0,91
St3 steel alloy[1]	4,0	0,15	0,58	0,68	0,79	0,84	0,88	0,89	—
St3 steel alloy[2]	2,0	0,05	0,52	0,53	0,54	0,62	0,85	0,87	—
St3 steel alloy[3]	3,0	0,07	0,32	0,42	0,46	0,75	0,89	0,91	—
40Chr2Ni2MoAl	3,0	0,17	0,50	0,53	0,56	0,59	0,63	0,64	0,64
19ChrMnNi2	5,0	0,15	0,49	0,53	0,53	0,60	0,80	0,94	—
38ChrNi3MnAl	6,0	0,22	0,49	0,50	0,53	0,57	0,67	0,76	—
AlMn[4]	1,5	0,15	0,36	0,44	0,44	0,40	—	—	—

[1]The surface was oxidized in concentrated chemically pure sulfuric acid for 55 min.
[2]The surface was ground on an emery wheel.
[3]The surface was oxidized in concentrated chemically pure hydrochloric acid for 55 min.
[4]The heating rate was 9 deg/min.

LITERATURE CITED

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DETERMINATION OF TRUE VALUES OF THE THERMAL CONDUCTIVITY OF INERT GASES AT ATMOSPHERIC PRESSURE AND TEMPERATURES FROM THE NORMAL BOILING POINT TO 6000°K

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True values of the thermal conductivity are calculated for neon, argon, krypton, and xenon over the temperature range from the normal boiling point to 6000°K at atmospheric pressure.

The thermal conductivity (λ) of gases and their mixtures is a fundamental physical constant. Knowledge of its precise value is of great practical and theoretical importance. The information available in the literature on the thermal conductivity of gases and their mixtures is not always of satisfactory quality, internally consistent, and free from errors related to various physical effects which distort the true value of the coefficient.

In experiment, no matter what method is used, one always measures an effective value of λ, which is not equal to the true value (by true we understand the quantity defining heat transfer due to a temperature gradient).

When the thermal conductivity of heavy inert gases is measured at low temperatures with the steady-state hot-wire method, elevated values of the coefficient are obtained, while determination of λ of inert gases by the shock-tube method gives reduced values (by up to 12%), and the thermal conductivity column method gives elevated (up to 3%) values compared to results of steady-state methods in overlapping temperature ranges.

In 1982 a table of standard reference data on transport properties of inert gases at atmospheric pressure for temperatures from the normal boiling point to 2500°K was developed in the USSR [1]. In our opinion, the thermal conductivity data presented in [1] require extension to a temperature of 6000°K.

In the temperature range from the normal boiling point to 1000°K the thermal conductivity of inert gases is usually measured by the steady-state plane layer or hot-wire methods, while from 1000 to 6000°K the nonsteady-state shock-tube method is used.

In processing the available experimental material on the thermal conductivity of inert gases obtained by the steady-state hot-wire and nonsteady-state shock-tube methods in overlapping temperature ranges, the authors of [2-4] observed that the data obtained with the second variant of the shock-tube method* are systematically low in comparison with the results of steady-state measurements (Table 1).

*The first variant of the shock-tube method is based on approximate solution of the nonlinear energy transport equation in a narrow temperature interval, based on the assumption that $\beta = (\lambda/\lambda_f)T_f/T$ is a constant quantity; the second variant consists of specifying the form of the temperature dependence of the thermal conductivity in the form $\lambda = \lambda_0(T/T_0)^b$, where b = const.

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