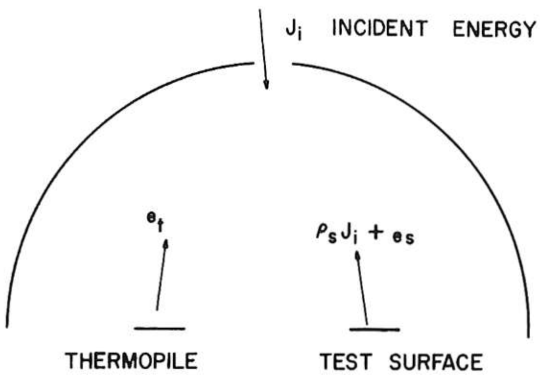

Fig. 5 Thermopile-energy balance

term is the energy originating at the thermopile itself which arrives back on the thermopile after reflection from the test surface.

If the aperture is now closed to external radiation so that J_i is zero, the energy arriving at the thermopile becomes

$$G(2s) = e_s \rho_m C_s + e_t C_s^2 \rho_m^2 \rho_s' \tag{3}$$

Solving Equations (2) and (3) for the reflectivity of the test surface ρ_s,

$$\rho_s = \frac{G(1s) - G(2s)}{J_i \rho_m C_s} \tag{4}$$

The same type of relation obviously holds for the reference surface (r)

$$\rho_r = \frac{G(1r) - G(2r)}{J_i \rho_m C_r} \tag{5}$$

By a combination of equations (4) and (5), the reflectivity ρ_s is obtained

$$\rho_s = \rho_r \left(\frac{C_r}{C_s}\right) \frac{G(1s) - G(2s)}{G(1r) - G(2r)} \tag{6}$$

A heat balance may now be written on the thermopile itself when it is receiving energy in the amount $G(1s)$, since at equilibrium this energy must be balanced by the energy lost by the thermopile surface by radiation, conduction, and convection:

$$G(1s) = \sigma T_{1s}^4 + k_1(T_{1s} - T_c) \tag{7}$$

where the first term on the right represents the radiation loss and the second term the convection and conduction losses. These losses can be assumed proportional to the difference between the temperature of the receiving surface and the temperature of the cold junction of the thermopile embedded in a metal block behind the receiving surface. Similarly we may write

$$G(2s) = \sigma T_{2s}^4 + k_1(T_{2s} - T_c) \tag{8}$$

From equations (7) and (8) it follows:

$$G(1s) - G(2s) = \sigma(T_{1s}^4 - T_{2s}^4) + k_1(T_{1s} - T_{2s}) \tag{9}$$

For small temperature differences, the first right-hand term can be linearized and combined with the second term to give

$$G(1s) - G(2s) = k_2(T_{1s} - T_{2s}) \tag{10}$$

A similar equation holds for the condition that the reference surface is in the test position. Therefore

$$\rho_s = \rho_r \left(\frac{C_r}{C_s}\right) \frac{(T_{1s} - T_{2s})}{(T_{1r} - T_{2r})} \tag{11}$$

The galvanometer reading Δ is, because of the small temperature differences involved, directly proportional to the temperature difference between the hot junction (T_{1s} or T_{2s}) and the cold junction T_c, which is maintained at a constant temperature. Therefore

$$\Delta(1s) = k_3(T_{1s} - T_c) \tag{12}$$

Similar expressions may be written for the other readings. This leads to the final equation

$$\rho_s = \rho_r \frac{C_r}{C_s} \frac{\Delta(1s) - \Delta(2s)}{\Delta(1r) - \Delta(2r)} \tag{13}$$

This equation may be simplified further since the reference material was selected to have similar directional reflection characteristics as the sample. Therefore $C_r = C_s$. The terms $\Delta(2s)$ and $\Delta(2r)$ in equation (13) have been found to be negligible since the test surface and thermopile cold junction were kept at the same temperature by the cooling water. The reflectivity was then calculated from the equations

$$\rho_s = \rho_r \frac{\Delta(1s)}{\Delta(1r)} \tag{14}$$

Surface Transmissivity. The data from the experimental procedure for transmitted energy can be analyzed in a manner similar to that for the reflected energy. Performing heat balances on the thermopile for both the incident i and transmitted τ energies and relating these to the thermopile output Δ result in the following expression for the transmissivity of the test surface:

$$\tau_s = \frac{\Delta(\tau)}{\Delta(i)}$$

where $\Delta(\tau)$ is the galvanometer reading with transmitted energy impinging on the thermopile and $\Delta(i)$ is the galvanometer reading with the total incident energy impinging on the thermopile.

DISCUSSION

M. N. Aref[4]

The authors are to be congratulated for contributing additional information on the radiation properties of porous fabrics. It appears from the comparison technique adopted by the authors that, in order to arrive at the absorptivity and hence the emissivity, direct measurements were obtained first on the reflectivity and transmissivity. The difference of both factors from unity determined the absorptivity. In this method, however, any errors involved in the calculation of the absorptivity will be due to the measurements of both reflectivity and transmissivity. It would be helpful to know the magnitude of such errors, which might be attributed to a possible heat loss through the radiometer aperture and an absorbed heat by the comparatively wide radiometer mirrored surface.

As is well known, however, the emissivity of a surface may not be equal to its absorptivity, unless its monochromatic absorptivity is considered independent of both radiation wave length and temperature. On the other hand, a direct measurement of the emissivity of such surfaces could be determined by either one of the two methods presented in an earlier paper by the writer,[5] with a slight modification of the apparatus for the normal solar radiation measurement. This is basically accomplished by placing a solar radiation or a black-body radiation source at the same temperature as the sample, at a fixed distance from the measuring radiometer, provided that both source and sample bear the same configuration to the radiometer. Both

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[5] M. N. Aref, "Emissivity Measurements of Industrial Surfaces Due to Thermal Radiation," Paper No. 58—HT-18, presented at ASME-AIChE Heat Transfer Conference, Chicago, Ill., August, 1958.

radiations from source and sample could then be directed at the radiometer separately and their ratio would render the emissivity directly, thus eliminating the sources of error in the measurements of the reflectivity and transmissivity.

Authors' Closure

The first two questions asked by Mr. Aref can be answered directly from the Analysis of Data section. The amount of energy lost through the aperture is taken into account by the factor C (amount of energy reaching thermopile from test surface divided by actual amount leaving test surface). Referring to previous work of the authors, Ref. [3] of the paper, the value of energy lost through the aperture for various surfaces varies from 1 to 4 per cent. The amount of energy absorbed by the hemispherical surface is also taken into account in the analysis by the factor $(1 - \rho_m)$.

The authors are well aware of available methods for directly measuring the total emissivity and indeed have made such measurements in the past.[6,7] However, if a radiometer is sighted on a porous surface such as a parachute fabric, the energy reaching the radiometer comes not only from the porous sample but additionally some energy is transmitted through the sample; it is extremely difficult to separate the emitted energy from the transmitted energy and, consequently, the authors chose to determine the absorptivity as outlined in the paper. Mr. Aref appears to have missed the point that the resulting measured absorptivity for infrared radiation coming from a black body at 350 F does indeed yield the emissivity if the monochromatic absorptivity is invariant with temperature (it can still vary with wave length). The proof is straightforward:

[6] E. R. G. Eckert, J. P. Hartnett, and T. F. Irvine, Jr., "Measurement of Total Emissivity of Porous Materials in Use for Transpiration Cooling," *Jet Propulsion*, vol. 26, 1956, p. 280.

[7] T. F. Irvine, Jr., J. P. Hartnett, and E. R. G. Eckert, "Solar Collector Surfaces With Wavelength Selective Radiation Characteristics," *Solar Energy Journal*, vol. II, July-Oct., 1958, p. 12.

Kirchhoff's law states that the spectral emissivity of a surface at a temperature T is equal to the spectral absorptivity at this same temperature

$$\epsilon_{\lambda,T} = \alpha_{\lambda,T} \tag{15}$$

The definition of the total absorptivity α of a surface at a temperature T_s for incoming radiation $J_{i\lambda}$:

$$\alpha = \frac{\int_0^\infty \alpha_{\lambda,T} J_{i\lambda} d\lambda}{\int_0^\infty J_{i\lambda}\, d\lambda} \tag{16}$$

The definition of the total emissivity of a surface at temperature T is given by

$$\epsilon = \frac{\int_0^\infty \epsilon_{\lambda,T}\, e_{b\lambda,T} d\lambda}{\int_0^\infty e_{b\lambda,T} d\lambda} \tag{17}$$

where

$e_{b\lambda,T}$ = amount of energy emitted by a black body at temperature T at wave length λ, Btu/hr ft²

Now in the infrared experiments described herein the incoming radiation $J_{i,\lambda}$ corresponded to black body radiation at 350 deg

$$J_{i,\lambda} = e_{b\lambda,\,350\text{ F}} \tag{18}$$

The surface temperature of the parachute material was approximately 100 F and, if it is assumed that the spectral absorptivity is independent of temperature,

$$\alpha_{\lambda,100\text{ F}} = \alpha_{\lambda,350\text{ F}} = \epsilon_{\lambda,350\text{ F}} \tag{19}$$

Substituting (18) and (19) into equations (16) and comparing with equation (17) it is readily seen that the measured absorptivity directly yields the emissivity.