Pergamon

Int. J. Heat Mass Transfer. Vol. 40, No. 1, pp. 61–71, 1997

0017-9310/97 $15.00+0.00

PII: S0017-9310(96)00071-3

The measurement and calculation of radiative heat transfer between uncoated and doped tin oxide coated glass surfaces

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(*Received* 26 *June* 1995 *and in final form* 13 *February* 1996)

Abstract—Accurate measurements are reported of the radiative heat transfer between parallel surfaces of uncoated and doped tin oxide coated glass. The infrared properties of the tin oxide coated glass are calculated by a novel approach by fitting a three parameter Drude model to reflectance measurements at a specified angle, and over a restricted range of wavelengths. Estimates of the radiative heat transfer between uncoated and coated glass surfaces are calculated from a consideration of the directional spectral emittances and the blackbody spectrum. This procedure gives results that are in more consistent agreement with experimental measurements than results obtained by considering the hemispherical total, or directional total emittances. Copyright © 1996 Elsevier Science Ltd.

INTRODUCTION

The calculation of the radiative heat transfer between surfaces is important in many practical situations including insulating glazing, radiative cooling and aerospace applications. This paper presents measurements and calculations of the radiative heat transfer between two plane parallel glass surfaces separated by a vacuum. The examination of this problem was motivated by the observation of discrepancies between calculated and accurate experimental values for radiative heat transfer between uncoated and coated glass surfaces.

It is known that radiative heat exchange between surfaces is dependent on the spectral, angular and temperature dependencies of the surface emittances, although the angular and wavelength dependencies are usually ignored in the elementary treatment of heat transfer [1]. A more sophisticated analysis involves an integration over wavelength of the surface emittance at each angle to give the directional total emittance for each surface. These angular dependent emittances are then combined conventionally and integrated over angle [2]. In this paper, it is shown that this method leads to errors which can be as large as those inherent in the elementary analysis. The radiative heat transfer between parallel surfaces is calculated by directly combining both the wavelength and angular dependencies of emittance in one integration step. This method gives an exact result for specularly reflecting surfaces, provided that the optical properties of the surfaces are known.

This paper also presents a novel approach to the determination of the optical properties of doped tin oxide coated glass. This method is validated by comparison with independent measurements of the wavelength and angular dependence of reflectance, and with thermal measurements of radiative heat flows with this type of glass. The glass coating is a pyrolitically deposited transparent conducting film that is commonly used in the glazing industry. The coated glass is known by a variety of trade names including 'K glass' [3], which is the brand considered in this study.

THEORY

The radiative heat transfer per unit area between two plane parallel grey surfaces of equal area at temperatures T_1 and T_2 can be written as [1]:

$$q = \varepsilon_{\text{eff}}\sigma(T_1^4 - T_2^4). \tag{1}$$

The quantity ε_{eff} is the effective emittance for the two surfaces and is often written as:

$$\varepsilon_{\text{eff}} = \left(\frac{1}{\varepsilon_{h,1}(T_1)} + \frac{1}{\varepsilon_{h,2}(T_2)} - 1\right)^{-1} \tag{2}$$

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NOMENCLATURE

A	surface area
C_{rad}	radiation conductance
d_f	film thickness
d_s	substrate thickness
DR	average deviation of reflectance
$E_\lambda(\lambda, T)$	spectral blackbody emissive power
k	extinction coefficient
N	total number of wavelengths used in equation (12)
n	refractive index
$\tilde{n}_f$	complex refractive index of film
n_s	complex refractive index of substrate
q	rate of radiative heat transfer per unit area
T	surface temperature
T_{ave}	average temperature of two emitting surfaces.

Greek symbols

$\alpha(\lambda, \theta)$	directional spectral absorbtance
$\varepsilon_h(T)$	hemispherical total emittance
ε_{eff}	effective emittance
$\varepsilon_{\theta,t}(\theta, T)$	directional total emittance
$\varepsilon_{\lambda,\theta}(\lambda, \theta, T)$	directional spectral emittance
λ	wavelength
θ	angle of incidence from the normal
$\rho(\lambda, \theta)$	directional spectral reflectance
σ	Stefan-Boltzmann constant
$\tau(\lambda, \theta)$	directional spectral transmittance
ω	frequency
ω_p	plasma frequency
ω_β	damping frequency
$\tilde{\zeta}(\omega)$	complex dielectric function
ζ_∞	contribution from high frequency band transitions.

Subscripts

ave	average
calc	calculated quantity
eff	effective
expt	experimental quantity
f	pertains to film
h	hemispherical
j	wavelength number in equation (12)
p	pertains to plasma
rad	radiation
s	pertains to substrate
1,2	denote surfaces for heat transfer
θ,t	directional total quantity
λ,θ	directional spectral quantity.

Superscript

$\tilde{}$	complex quantity.

where $\varepsilon_{h,1}(T_1)$ and $\varepsilon_{h,2}(T_2)$ are the hemispherical total emittances of the surfaces at the specified temperatures. This relationship is valid only for surfaces with no wavelength and directional dependence for the emittances.

According to the ISO 10292 standard [4], the radiative heat transfer between plane parallel glass surfaces should be calculated with a radiative conductance, which can be derived from a Taylor series expansion of equation (1):

$$C_{rad} = 4\varepsilon_{eff}\sigma T_{ave}^3 \quad (3)$$

where T_{ave} is the average of the surface temperatures, and the effective emittance is determined by equation (2). In this standard, the hemispherical emittances of equation (2) are referred to as "corrected emissivities." The corrected emissivity for uncoated glass is the hemispherical emittance (taken to be 0.837), and that for coated glass surfaces is determined by multiplying the normal emittance by a coefficient given in the standard. For the temperature differences considered in this paper, the heat flows calculated using a radiative conductance [equation (3)] differ by less than 0.1% from those obtained using equation (1). Thus, the two approaches are equivalent to within this error.

It is instructive to calculate the hemispherical total emittance of a single surface in two steps [5]. Firstly, the directional total emittance, $\varepsilon_{\theta,t}(\theta, T)$, is determined by evaluating an integral over wavelength of the directional spectral emittance, $\varepsilon_{\lambda,\theta}(\lambda, \theta, T)$, multiplied by the spectral blackbody emissive power at the given temperature, $E_\lambda(\lambda, T)$:

$$\varepsilon_{\theta,t}(\theta, T) = \frac{\int_0^\infty \varepsilon_{\lambda,\theta}(\lambda, \theta, T) E_\lambda(\lambda, T)\, d\lambda}{\int_0^\infty E_\lambda(\lambda, T)\, d\lambda}. \quad (4)$$

In the second step, this directional total emittance is integrated over the hemisphere, assuming that the emittance is a function of only the cone angle, θ (measured from the normal to the surface), of the solid angle of view:

$$\varepsilon_h(T) = \int_0^{\pi/2} \varepsilon_{\theta,t}(\theta, T) \sin(2\theta)\, d\theta. \quad (5)$$

A commonly used method for calculating the effective emittance for plane parallel glass surfaces follows a similar procedure: the hemispherical total emittances in equation (2) are replaced by directional total emittances, obtained by experimental measurements, or by an integral as in equation (4). The effective emittance is then evaluated by integrating over angle these directional total emittances:

$$\varepsilon_{\text{eff}} = \int_0^{\pi/2} \left(\frac{1}{\varepsilon_{\theta,t,1}(\theta)} + \frac{1}{\varepsilon_{\theta,t,2}(\theta)} - 1 \right)^{-1} \sin(2\theta)\, d\theta \tag{6}$$

where the temperature dependence of the directional total emittance is assumed to be negligibly small. This equation gives the correct effective emittance for grey surfaces. The effective emittance is then substituted into equation (1) in order to obtain the radiative heat transfer. This is the approach accepted in studies of emittance properties of glass surfaces by van Nijnatten [2], Silva and Jones [6] and Geotti-Bianchini and Lohrengel [7].

Equation (2) can be derived from a consideration of the net energy absorbed and reflected by each surface. This equation is correct only in the case where the optical properties of each surface are independent of wavelength and angle. The derivation of this equation can be generalized to include wavelength and angular dependencies of emittance for the case of specular surfaces by defining an effective directional spectral emittance of the form of equation (2) at a specific wavelength, λ, and angle, θ, by replacing $\varepsilon_h(T)$ with $\varepsilon_{\lambda,\theta}(\lambda, \theta, T)$. The overall heat flow from one surface is obtained by an integral over wavelength and over all angles, using the blackbody spectrum at the temperature of the surface. The net heat transfer between the two surfaces is the difference between two such quantities at the respective surface temperatures:

$$q = \int_0^{\pi/2} \int_0^{\infty} \frac{[E_\lambda(\lambda, T_1) - E_\lambda(\lambda, T_2)]}{\dfrac{1}{\varepsilon_{\lambda,\theta,1}(\lambda, \theta, T_1)} + \dfrac{1}{\varepsilon_{\lambda,\theta,2}(\lambda, \theta, T_2)} - 1} d\lambda \times \sin(2\theta)\, d\theta. \tag{7}$$

In the evaluation of equation (7), the range of wavelengths for the integration is determined by the blackbody spectrum. For this work, a range of 1–50 μm is appropriate for the temperatures of interest. According to Rubin [8], the hemispherical total emittance of glass is only weakly dependent on temperature ($d\varepsilon_h(T)/dT \sim 10^{-4} K^{-1}$), which is also true of most dielectrics. In this study, the directional spectral emittances are calculated on the basis of optical properties measured at room temperature since the temperature dependence of the directional spectral emittance is so small over the range of temperatures considered (3°C–53°C).

CALCULATION OF THE DIRECTIONAL SPECTRAL EMITTANCE OF UNCOATED AND COATED GLASS

Figure 1(a) shows that for radiation incident upon a glass surface at an angle θ, some of the radiation is reflected from, absorbed by, or transmitted through the glass. The directional spectral reflectance, absorbtance and transmittance, $\rho(\lambda, \theta)$, $\alpha(\lambda, \theta)$ and $\tau(\lambda, \theta)$, are related by:

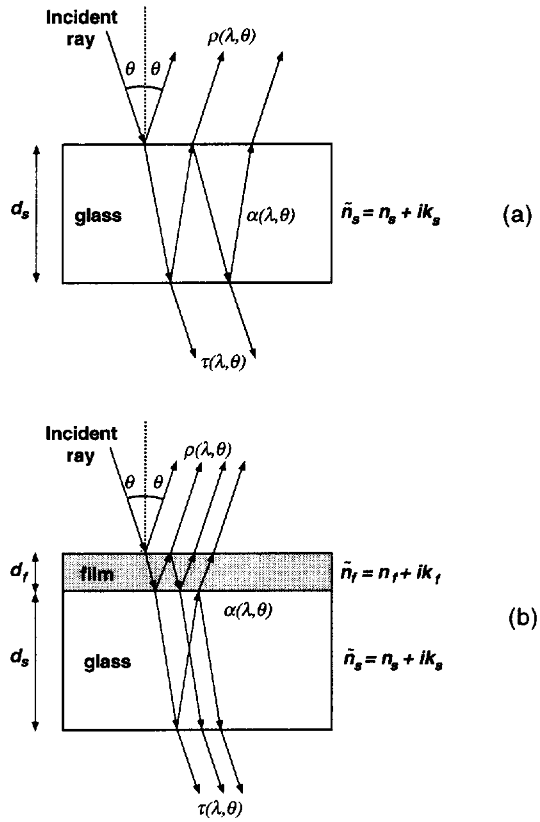

Fig. 1. Radiation incident upon a surface, in (a) for a plain glass surface, and in (b) for a thin film on glass substrate. Only a few ray tracings are shown to demonstrate the multiple specular reflection at each boundary.

$$\rho(\lambda, \theta) + \alpha(\lambda, \theta) + \tau(\lambda, \theta) = 1. \tag{8}$$

By Kirchoff's Law, the absorbtance equals the emittance so that the directional spectral emittance is:

$$\varepsilon_{\lambda,\theta}(\lambda, \theta) = 1 - [\rho(\lambda, \theta) + \tau(\lambda, \theta)]. \tag{9}$$

The directional spectral reflectance and transmittance can be calculated from the complex refractive index ($\tilde{n} = n + ik$) and the thickness of the glass [9, 10]. Although not written as such, the complex refractive index is a function of wavelength. The indices n and k for clear float glass, evaluated from reflectance measurements of a sample at 20°C, are tabulated by Rubin for wavelengths in the infrared [8].

For a film on a thick glass substrate, the analysis is much more complicated because there is reflectance at each interface, and absorbtance and transmittance for each layer. Figure 1(b) shows such a bi-layer system, where the film is doped tin oxide of thickness d_f and the substrate is glass of thickness d_s. The calculation of the directional spectral emittance of the system requires a knowledge of the thickness and complex refractive index for each layer. While the complex refractive index for glass is known from Rubin's data, there is little information about that for the particular doped tin oxide film considered in this study.

The complex refractive index for doped tin oxide on glass could be determined by applying the Kramers–Krönig formula to reflectance measurements of the film. However, this method is only useful for films of sufficient thickness to ensure that there is a negligible contribution from the substrate to the total reflectance. For the present study of doped tin oxide coated glass, a coating thickness of a few micrometers would be required. However, the coating is approximately 0.3 μm thick and hence this method cannot be used. The refractive index could also be determined from measurements of reflectance and transmittance for the bi-layer system, but since glass has a low transmittance for $\lambda > 5$ μm [8], this method cannot be used over most of the infrared region. Van Nijnatten and Simonis [11] assume that n and k for doped tin oxide are independent of wavelength in the infrared; they selected values which, when substituted into the Fresnel equations, gave total directional emittances which best agreed with experimental values. This assumption has no true physical basis and provides a poor fit to the experimental emittance data at high angles. A novel method for calculating the complex refractive index for doped tin oxide, based on the Drude model [12, 13], is proposed below.

The Drude model relates the optical and electrical properties of conductors. It can also relate these properties for semiconductors, such as doped tin oxide, in the infrared. The complex dielectric function for semiconductors, $\tilde{\zeta}(\omega)$, can be described by the Drude model for free carriers as:

$$\tilde{\zeta}(\omega) = \zeta_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\omega_\beta} \tag{10}$$

where ω is the frequency, ζ_{∞} is the low frequency contribution from the high frequency interband transitions, ω_p is the plasma frequency and ω_β is the damping frequency [12]. The complex refractive index is equal to the square root of the complex dielectric function [14]:

$$\tilde{n}_f = n_f + ik_f = \sqrt{\tilde{\zeta}}. \tag{11}$$

The directional spectral reflectance and transmittance for doped tin oxide coated glass can be calculated from the thicknesses and complex refractive indices of both the coating and the substrate by a matrix formulation approach derived from Maxwell's equations [9, 10]. The directional spectral emittance is then calculated by equation (9). The method for first determining the complex refractive index of the doped tin oxide coating, $\tilde{n}_f$, is presented below.

The spectral reflectance for the doped tin oxide coated glass is measured at an angle of incidence of 10° over 2.5–25 μm as described in the next section. The reflectance spectrum for the same angle of incidence is calculated as follows. Initial values are set for ζ_{∞}, ω_p and ω_β which are substituted into equation (10) to evaluate the complex dielectric function which is then substituted into equation (11) to give the complex refractive index. This refractive index, together with that for glass and the measured film and substrate thickness, are then used to calculate $\rho(\lambda, 10°)$ and $\tau(\lambda, 10°)$ for the system. The calculated and measured reflectance values are compared by an analysis of the deviations between the results at certain wavelengths:

$$DR = \sqrt{\left(\sum_{j=1}^{N} \{[\rho_{calc}(\lambda_j, 10°) - \rho_{expt}(\lambda_j, 10°)] / \rho_{expt}(\lambda_j, 10°)\}^2\right) / N} \tag{12}$$

where DR is the average deviation, j refers to the different wavelengths, N is the total number of wavelengths compared, and ρ_{calc} and ρ_{expt} are the calculated and experimental reflectance values at each specified wavelength. Typically 10–15 wavelengths are selected between 3 and 17 μm. This entire procedure is reiterated until DR is minimized. For each iteration, the Drude formula parameters ζ_{∞}, ω_p and ω_β are re-estimated by a computer subroutine of the downhill simplex method in multidimensions [15]. The final results for the three parameters of the Drude formula are then substituted into equation (10). The resulting complex dielectric function is substituted into equation (11), from which the complex refractive index for the doped tin oxide coating is evaluated over wavelengths between 1 and 50 μm. The above procedure can be performed on measurements taken at other angles of incidence. It was also used to obtain the Drude formula parameters from spectral reflectance measurements at an angle of incidence of 70°.

The doped tin oxide coating is highly inhomogeneous through its thickness and thus, an accurate determination of the optical constants requires the use of a complex gradient index model [16]. However, the physical model presented above is based on the assumption that the doping concentration does not vary significantly through the thickness of the glass coating. Therefore, the optical properties for K glass that are determined with this model should be thought of as effective properties. The justification for this simplistic approach rests on the agreement obtained between the calculated and experimental reflectance data over a wide range of wavelengths and angles.

EXPERIMENTAL

Reflectance spectra at near normal incidence (10°) were measured with a Shimadzu IR-470 infrared spectrophotometer over the wavelength range of 2.5–25 μm. The calibration standard for this measurement is a freshly evaporated copper film on a glass substrate, the infrared near-normal reflectance of which is taken to be 0.990. This estimate is based on a calibration with a Cary 5 spectrophotometer in the region of 0.25–

3 μm, and on independent comparative measurements of a polished copper surface [17].

High angle reflectance measurements were made with a Fourier transform spectrophotometer (Bruker IFS 66) over the wavelength range of 0.3–14 μm. Attached to this spectrophotometer are a polarizer, analyser and goniometer [18]. These measurements were performed for s- and p-polarization, i.e. with the polarizer and the analyser in the s- and p-directions. Results for the two polarizations were averaged, and it is these averaged data that are presented in this paper. Corresponding near normal measurements (at an angle of incidence of 8°) were made with an integrating sphere.

Thermal measurements of the radiative heat transfer between different surfaces were made with two guarded hot plates of different areas. Figure 2 is a schematic diagram of the configuration of the larger area hot plate and the evacuated sample. The glass plates are sealed around the edges with a rubber gasket, and the internal gap of 1.0 mm is evacuated to a pressure below 10^{-1} Pa. The configuration for the small area apparatus is similar, and has been described previously [19]. The separation of the glass plates under the influence of atmospheric pressure, is maintained with several small support pillars. The principle of the guarded hot plate is well known: a thermal conductor (called the metering piece in this paper), and a surrounding isothermal guard are placed in good thermal contact with one side of the sample, and the other side is maintained at a constant lower temperature. Power is supplied to the metering piece to make its temperature precisely equal to that of the guard. Under this null condition, this power is equal to the heat flow through the sample from the metering piece.

There are significant challenges in the application of this principle to the accurate measurement of the radiative heat flow between two parallel glass sheets. The necessity for both the metering piece and the guard to be in good thermal contact with a glass plate means that they are also in good thermal contact with each other. This has several important experimental consequences. Firstly, high accuracy measurements require the detection of very small temperature differences between metering piece and guard ($\sim 10^{-4}$ K in this case). Secondly, the heat flow at the null condition does not necessarily correspond to the area defined by the mid-point of the gap between the metering piece and the guard. This effective area is quite strongly dependent on the co-planarity of the surfaces of the components which contact the sample. Thirdly, the guard must be large enough so that lateral parasitic heat flows along the hot glass plate to the surroundings are negligible. Fourthly, the small support pillars between the glass plates must be located sufficiently far from the measurement region for heat flow through them, to be negligible. Finally, the size of both guarded hot plates is quite small: the metering pieces are 46 mm and 13 mm in diameter for the large and small devices with corresponding annular gaps of 0.5 mm and 1.0 mm, respectively. The absolute amount of heat flow which needs to be detected in high accuracy measurements is thus also very small. It is therefore essential to pay very careful attention to the thermal termination of the electrical leads which are connected to the metering piece.

Several aspects of the design of this type of apparatus, including sensitivity, parasitic heat flows and the effect of pillars, have been discussed previously [19]. A critical issue for the present discussion is the calibration of the large area hot plate. Full details of this procedure will be presented in a future paper. In brief, the effective calibration was determined through detailed finite element modelling, including the effects of the gap, the co-planarity of the metering piece and guard, and the location of the temperature sensors in these components. The effective area of this apparatus, as determined by these procedures is 1.702×10^{-3} m^2.

The geometry of the small area apparatus is much less well defined. This apparatus was therefore calibrated by direct measurement of a sample of known conductance, as discussed below.

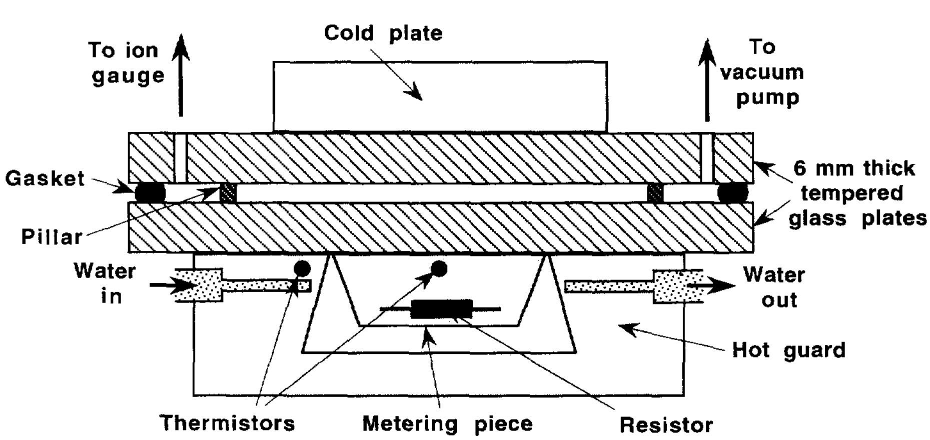

Fig. 2. Schematic diagram of the large area guarded hot plate apparatus and sample configuration for measurements of radiative heat flow between parallel glass surfaces.

In all measurements of radiative heat flow between the evacuated inner surfaces of the glass plates, an allowance was made for the temperature difference across the thickness of the glass. Due to the opacity of glass at wavelengths greater than 5 μm, the thickness of the glass sheets, and the distance between the pillars and the metering piece, it may be assumed that in the measurements with both guarded hot plates there is negligible heat transfer across the evacuated space from any processes except radiation from the internal glass surfaces of the samples.

Infrared measurements with the Shimadzu spectrophotometer indicated significant variations (approx 10%) in the point-to-point reflectance at 2.5 μm of K glass samples. Comparative optical and thermal measurements were therefore made at the same locations on each sample. This spatial variation in the reflectance (and thus the emittance) necessitates the use of the small area guarded hot plate apparatus for accurate comparative measurements on K glass, as the area measured by the Shimadzu spectrophotometer (about 1×10^{-4} m^2) is of the same order as the measurement area of this guarded hot plate apparatus. The reflectance of uncoated glass is highly uniform, and thus variations over the area of the metering piece of the large area guarded hot plate are negligible.

The thickness of the glass was measured with a micrometer and the thickness of the film was measured with a Tencor P-10 surface profiler. In the measurements, total glass thicknesses for the samples on both guarded hot plates ranged between 6 and 8 mm. Calculations presented below are for glass thicknesses of 4 and 6 mm, and a film thickness of 0.33 μm. Due to the opacity of glass at wavelengths greater than 5 μm, the hemispherical emittance of uncoated glass thicker than 4 mm is virtually independent of thickness; modelling results show that the hemispherical emittances of 4 and 20 mm thick glass differ by only 0.1%. Therefore, it is valid to compare calculated heat flows for 4 mm thick glass sheets with thermal measurements on slightly thicker glass sheets.

RESULTS

In this section, the error associated with the method of calculating the directional spectral emittance of K glass is discussed. Results are then presented that validate this method of calculation. Estimates of the heat flows between various combinations of uncoated glass and K glass surfaces are given, as calculated by three different methods. A comparison between the calculated heat flows and experimental data enables conclusions to be drawn about the accuracy of the methods of calculation.

The greatest source of error associated with the calculated emittances for K glass is the error in the reflectance measurements on which they are based. As noted above, the reference standard for the Shimadzu spectrophotometer is a copper film with a spectral reflectance of 0.990. The error for the reference measurement, including that involved in the assumption of a constant reflectance in the infrared, is about ± 0.005. For the measurements on K glass, this is only a 0.6% error in the average reflectance of 0.8, but it represents a 2.5% error in the corresponding calculated average emittance of 0.2. Thus, for K glass surfaces, the error associated with the evaluated emittances, and therefore with the calculated heat flows, is taken to be $\pm 2.5\%$.

Figure 3 shows the experimental measurements of the spectral reflectance of K glass at an angle of incidence of 10°, obtained with the Shimadzu infrared spectrophotometer. The spectral reflectance calculated by the Drude formula described above is shown in this figure as a dashed line. The Drude parameters for the calculated results are: $\omega_p = 1.51 \times 10^4$ cm^{-1}, $\omega_\beta = 1.66 \times 10^3$ cm^{-1}, and $\zeta_\infty = 7.5$. The measurements obtained with the Shimadzu infrared spectrophotometer at this angle of incidence were independently confirmed with data from the above mentioned integrating sphere at an angle of incidence of 8°. This comparison is valid since there is negligible variation of reflectance with angles of incidence of less than 20°, and only a small and gradual angular dependence for angles up to approximately 70° [11].

Figure 4 presents the spectral reflectance for another sample of K glass measured at different angles of incidence using the fourier transform spectrophotometer. Also shown in this figure, as dashed lines, are results calculated from the Drude formula parameters derived from the reflectance spectrum for an angle of incidence of 70° in the manner described above. This comparison is done at high angles of incidence because the directional dependence of the emittance of K glass is much greater at higher angles. The Drude parameters for the calculated results are: $\omega_p = 9.74 \times 10^3$ cm^{-1}, $\omega_\beta = 7.03 \times 10^2$ cm^{-1}, and $\zeta_\infty = 3.3$. The parameters for this sample are somewhat different from those of the sample considered in Fig. 3. This is probably due to variations in the composition of, or the manufacturing process for the film; as mentioned previously, the point-to-point emittance of K glass has been observed to vary by as much as 10%, which indicates significant changes in the nature of the film.

In Figs. 3 and 4, there is a dip in the reflectance at 8 μm, which is associated with the change in reflectance of the glass substrate near this wavelength. There are small differences between the two sets of results in Fig. 4 at about 2 μm, the origin of which is unknown. However, in both figures, there is generally a very good agreement between the experimental and calculated results. This validates the method of determining the directional spectral reflectance (and thus the emittance) of doped tin oxide coated glass. In particular, the assumption that there is no significant gradient through the thickness of the film leads to an adequate representation of the optical properties in the thermal infrared region.

Having established the validity of the technique of

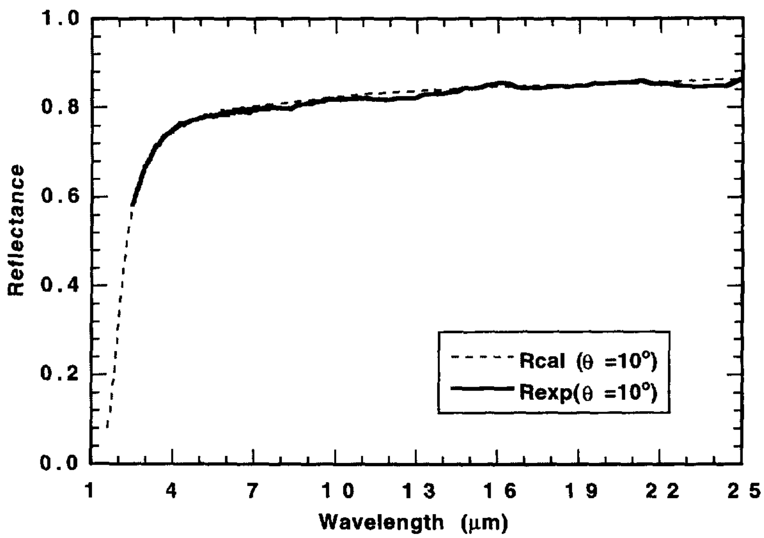

Fig. 3. The spectral reflectance for K glass at a 10° angle of incidence. Experimental results measured with the Shimadzu infrared spectrophotometer (full line) are compared with calculated results (dashed line).

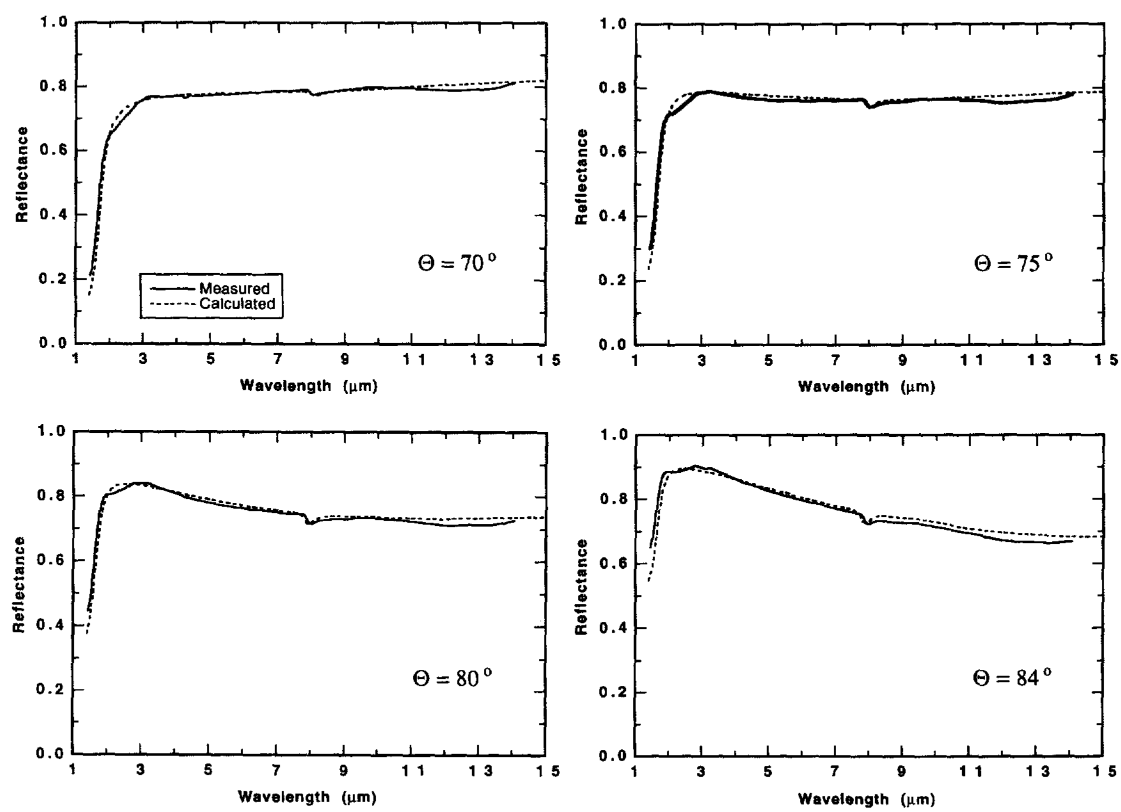

Fig. 4. The spectral reflectance for K glass at different angles of incidence, θ. Experimental results measured with the Fourier spectrophotometer (full lines) are compared with calculated results (dashed lines).

predicting the emittance of K glass, heat transfer results may now be considered. Table 1 lists the measured and calculated heat flows per unit area between uncoated glass surfaces at the given temperatures. The measurements were made on tempered glass with the large area guarded hot plate apparatus. The calculated heat flows are determined by three different methods. For method 1, the effective emittance is determined by equation (2), using a hemispherical total emittance of 0.838, as determined by equations (4) and (5). This hemispherical total emittance is only 0.1% greater than that quoted in the ISO standard: 0.837. The effective emittance is then substituted into equation (1) to calculate the heat flow. As noted above, this approach gives results which are essentially identical to the ISO method which uses equation (2) in con-

Table 1. Heat transfer per unit area between uncoated glass surfaces for the temperatures indicated, calculated by different methods. For method 1, the heat flow is calculated on the basis of a simple combination of the hemispherical total emittances [equations (1) and (2)]. For method 2, the heat flows are based upon an integration over angle of the directional total emittances [equations (6) and (1)]. In method 3, the heat flows are calculated by an integration over wavelength and angle of the directional spectral emittances and the spectral blackbody emissive powers (equation (7)). The experimental measurements were taken with the large area guarded hot plate

	Heat flow, q(W m^{-2}) Surface temperatures 4.01/22.81°C	Surface temperatures 34.27/52.68°C
Calculated		
Method 1	72.3 ± 0.6	96.2 ± 0.9
Method 2	73.0 ± 0.7	97.1 ± 0.9
Method 3	75.4 ± 0.7	101.1 ± 0.9
Measured	75.2 ± 0.4	100.5 ± 0.8

junction with a radiative conductance. Thus, method 1 is equivalent to the ISO standard. In method 2, the effective emittance is determined by an integration over angle as given by equation (6) and this emittance is then substituted into equation (1) to calculate the heat flow. For the third method, the heat flow is calculated in one step by equation (7), with the integration performed over both wavelength and angle.

The calculated results of Table 1 are based on Rubin's optical constants [8], for which the associated error is related to the accuracy of the reference standard used for the reflectance measurements on which these constants are based. Individual emittances based on these constants are estimated to be accurate to $\pm 0.5\%$ [16]. All three methods calculate the heat flow based on a combination of emittances of a form similar to that of equation (2). Taking the average emittance for these combinations to be equal to the calculated hemispherical total emittance of 0.84 ($\pm 0.50\%$) leads to an error in the calculated heat flows of approximately $\pm 0.9\%$. The error associated with heat flow measurements with the large area guarded hot plate apparatus is estimated to be $\pm 0.5\%$. It is noted that the calculated results are based on Rubin's optical constants for untempered glass, whereas the large area guarded hot plate measurements are made on tempered glass. According to Rubin, all window glass has the same emittance to the third decimal regardless of tempering, tinting or most other treatments [16]. Thus, it is valid to compare the calculated and measured heat flows of Table 1. For the surface temperatures of 4.01/22.81°C and 34.27/52.68°C, the experimental results differ significantly from those obtained by methods 1 and 2. However, for both temperature ranges, the experimental results are in good agreement with the results obtained from equation (7). Thus it is concluded that, to within the respective errors, equation (7) provides results that are more consistent with the measured heat flows. This provides a validation of the use of this equation for calculating the radiative heat transfer between glass surfaces.

Measurements were also made of the radiative heat transfer between surfaces of K glass. As discussed above, in order to reduce the effect of the point-to-point variations in the emittance of K glass, these measurements must be made with the small area guarded hot plate apparatus. Because of the larger uncertainties associated with the dimensions of this apparatus, it was calibrated by comparison of measured and calculated absolute heat flows for a reference standard of two sheets of untempered and uncoated glass separated by an evacuated space. This was chosen as the reference because the thermal conductance for such a sample can be accurately calculated on the basis of Rubin's data [8]. This calculation was done with equation (7) because, as shown in Table 1, heat flows determined with this equation are in consistent agreement with the experimental results from the large area guarded hot plate. This calibration of the effective area has the effect of defining the measured radiative heat flow between two uncoated surfaces to be precisely equal to that predicted by equation (7). The effective area obtained in this way is 1.45×10^{-4} m$^2 \pm 1.0\%$. In comparing the calculated and experimental heat flows per unit area, the accuracy of the measured temperature difference across the sample must be considered. As the heat flow is roughly proportional to this temperature difference, the error associated with this difference ($\pm 0.4\%$) is added to that associated with the effective area to give a total accuracy of $\pm 1.4\%$ for the measured heat flow per unit area.

It should be noted that the experimental and calculated heat flows used for the above calibration correspond to different types of clear glass which are, respectively, that made by Pilkington (Australia) Limited, and that of a different manufacture studied by Rubin. Comparison of the near-normal reflectance spectra of these two glasses shows that the hemispherical total emittances differ by, at most, 0.5%. This is equal to the error associated with the emittance of Rubin's glass, and it is less than the error associated with the emittance of the Australian glass ($\pm 0.6\%$). It is therefore appropriate to use Rubin's data to calculate heat flows for comparison with heat flow measurements on the Pilkington (Australia) Limited product.

Table 2 lists measured and calculated per unit area heat flows for all possible combinations of uncoated glass and K glass. The experimental results were obtained with the small area guarded hot plate apparatus, and the calculated results were obtained by the same three methods described above. For method 1, the effective emittance was calculated from equation (2); the hemispherical total emittances for this equation were calculated from a combination of equations (4) and (5), using optical parameters for K glass deter-

Table 2. Heat transfer per unit area between various combinations of uncoated glass and K glass surfaces, for the indicated glass surface temperatures. The calculated results were determined by the same three methods described for Table 1. The experimental measurements were taken with the small area guarded hot plate. The effective and hemispherical emittances were determined by equations (1) and (2), respectively

Sample		Surface temperatures (°C)		Heat flows ($W\ m^{-2}$) Calculated				Emittance from $q = \varepsilon_{eff}\sigma(T_1^4 - T_2^4)$, $\varepsilon_{eff} = (\varepsilon_1^{-1} + \varepsilon_2^{-1} - 1)^{-1}$		
Side 1	Side 2	T_1	T_2	Method 1	Method 2	Method 3	Measured	ε_{eff}	ε_1	ε_2
Glass	Glass	22.72	3.75	72.1±0.6	72.8±0.6	75.2±0.7	75.2±1.1	0.746	0.855	0.855
K glass	K glass	23.12	3.33	12.6±0.3	11.5±0.3	12.1±0.3	11.9±0.2	0.113	*0.203*	0.203
K glass	Glass	23.08	3.37	20.0±0.5	19.4±0.5	20.1±0.5	19.5±0.3	0.186	*0.192*	0.855

mined from optical measurements and the Drude model in the previously described manner. All thermal and optical measurements were made at the same locations on the same samples of glass.

As discussed above, the heat flows shown in Table 2 for two uncoated glass surfaces as predicted by methods 1 and 2 are clearly inconsistent with the experimental result. The exact agreement between this experimental heat flow and that obtained by method 3 is due to the fact that the latter was used to calibrate the area with which the former was determined; as previously mentioned, as a result of the calibration procedure for the apparatus, these two heat flows are defined to be equal.

The heat flows given in Table 2, as calculated by methods 2 and 3, for two K glass surfaces are in better agreement with the experimental results than with those calculated by method 1. For this combination of surfaces, the effective emittance differs significantly from that of either surface. For the heat flow between K glass and glass surfaces, the predictions by all methods are nearly identical and are consistent with the experimental data. This is as expected since, for this combination of surfaces, the effective emittance is quite close to the hemispherical total emittance of K glass. Relative to the K glass, the glass is a reasonably black surface. For the heat flow between a low emittance surface and a perfectly black surface (for which the hemispherical total emittance is 1), all methods give identical results.

Table 2 also shows that the effective emittances calculated from the given heat flows and temperatures by equation (1). The hemispherical total emittances are then calculated from these effective emittances using equation (2). The glass and K glass hemispherical total emittances are calculated from the results for glass/glass and K glass/K glass samples and are found to be 0.855 and 0.203, respectively. For the K glass/glass arrangement, the hemispherical total emittance for K glass is determined from equations (1) and (2) using that for glass of 0.855. The result of 0.192 is 5% lower than that obtained from equations (1) and (2) for the sample of two sheets of K glass. Since this discrepancy is much greater than the experimental error, it is once again apparent that equations (1) and (2) (and thus the basis for the ISO method) do not provide a reliable approach for calculating the radiative heat transfer between these surfaces. The value of 0.855 given above for the hemispherical total emittance of uncoated glass differs significantly from the value of 0.837 given in the ISO standard, and by Rubin [8]. This is simply a reflection of the error intrinsic in the use of equations (1) and (2) to calculate the radiative heat transfer.

The conclusions drawn here about the validity of the different methods of calculation depend on the linearity, with respect to temperature, of the heat flows measured with the small area guarded hot plate apparatus. This linearity can be demonstrated by comparing the measured and calculated heat flows for different temperatures across the sample. Figure 5(a) is a plot of the radiative heat flow (i.e. the measured null power) between two K glass surfaces measured with the small area guarded hot plate apparatus as a function of $T_1^4 - T_2^4$. The data points can be approximated by a quadratic fit passing through the origin. The linear portion of such a fit is shown in this figure to demonstrate that the data have a slightly downward trend from this reference line. Figure 5(b) is a plot of the deviations of the data points from the linear portion of the quadratic fit. Also plotted are the deviations predicted by equation (7) based on the Drude formula parameters obtained from optical measurements on the same samples of K glass. These two sets of results agree to within the reproducibility of the experimental heat flows: $\pm 10\ \mu W$. Comparable agreement was obtained for the same analysis of the heat flows between two uncoated glass surfaces, and between K glass and uncoated glass surfaces. It should be noted that the measured deviations are near the limit of the resolution of the apparatus. However, there is generally a good agreement between the measured and calculated heat flows. This demonstrates that the null power of this instrument is indeed proportional to the heat flow through the sample over a wide range of powers.

CONCLUSION

This work was motivated by discrepancies which had been observed between accurate measurements and calculations of radiative heat transfer between

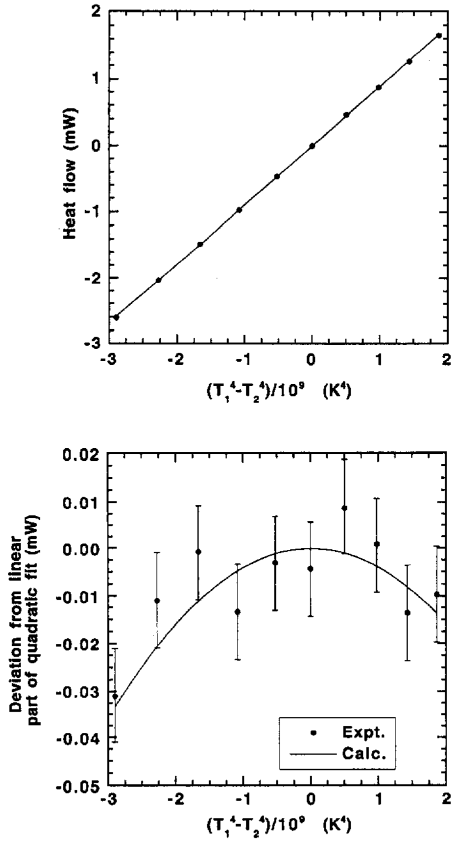

Fig. 5. Measured radiative heat flows (points) between two coated glass surfaces as a function of $T_1^4-T_2^4$ are shown in (a), along with the linear portion of a quadratic fit to the data (solid line). The data exhibit a downward trend in the deviations from this line. In (b), deviations from the linear portion of a quadratic fit to the data of the upper graph (points with ± 10 μW error bars) are plotted along with calculated deviations based on the optical properties of the K glass (solid line).

plane parallel uncoated and coated glass surfaces using simple, but commonly accepted formulae. The explanation of these discrepancies led to a detailed examination of methods of calculating radiative heat flow. It also required a novel technique for determining the infrared optical properties of glass coated with doped tin oxide.

It has been shown that the Drude model, which relates the optical and electrical properties of conductors, gives an accurate description of the infrared reflectance of a pyrolitically deposited transparent conducting layer of doped tin oxide, such as that on Pilkington K glass. Measurements of near-normal reflectance of K glass for wavelengths between 3 and 17 μm are used to obtain a best fit for the three parameters of the Drude model. This model then provides an estimate of the directional spectral emittance in the infrared. The calculated spectral reflectance data are in excellent agreement with experimental results measured to 84° from the normal to the surface.

The radiative heat transfer between plane parallel surfaces of uncoated glass has been calculated using estimates of the effective emittance determined by three methods: a simple combination of the hemispherical total emittances; and integration over angle of the directional total emittances; and an exact method involving a double integral of the wavelength and angular dependencies of the emittances of the surfaces. To within the range of the respective errors ($\pm 1.4\%$), the results of the third method agree with accurate large area guarded hot plate measurements of the radiative heat flow between plane parallel uncoated glass surfaces. The first two methods underestimate the heat flow by 5% and 4%, respectively.

Measurements, made with a small area guarded hot plate, of heat flow between combinations of uncoated and coated glass surfaces are, to within the estimated uncertainties, in agreement with results calculated by this third, exact method, and by the second of the two approaches described above; the one involving an integration over angle. These small area measurements indicate that the ISO standard method for calculating the radiative heat transfer between *uncoated* glass surfaces is in error, but it gives quite accurate results for other combinations of surfaces. The principal source of error in this comparison with coated glass surfaces is the reflectance from the copper film used as the reference for the infrared reflectance measurements from which the parameters of the Drude model are determined.

Experimental measurements of radiative heat transfer between glass surfaces as a function of the difference in the surface temperatures show small but significant deviations from the classical $T_1^4-T_2^4$ linear relationship due to the wavelength and angular dependencies of the optical properties of the surfaces. These deviations are consistent with the results obtained using the exact method of calculating the radiative heat transfer. This validates the linearity of the small area guarded hot plate measurement apparatus.

This work has significance for the accurate estimation of radiative heat transfer, particularly for insulating glazing. The method of calculation requires a detailed knowledge of the wavelength and angle dependent optical properties. Measurements of infrared reflectance as a function of temperature should permit the inclusion of the explicit temperature dependence of the optical properties of the materials under study. This was ignored in this analysis because, for the range of temperatures considered, it could be assumed that the temperature dependence of the directional spectral emittance is negligible.

Acknowledgements—This research was supported by his Royal Highness Prince Nawaf bin Abdul Aziz of the Kingdom of Saudi Arabia through the Science Foundation for Physics within the University of Sydney, and by the Australian Energy Research and Development Corporation. We acknowledge with thanks contributions by J-Z. Tang, H. Haldane, T. Pfeiffer and G. Mannes. This work was carried out (in part) as a contribution to the work of the International Energy Agency Solar Heating and Cooling

Programme, Task 18 Advanced Glazing Materials. The authors thank Dr M. Rubin of Lawrence Berkeley Laboratory for his helpful comments.

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